

PROCEEDINGS
OF THE
AMERICAN ACADEMY
OF
ARTS AND SCIENCES

VOL. LXXVI

INCLUDING RECORDS
FROM OCTOBER 1944 TO MAY 1948



BOSTON:
PUBLISHED BY THE ACADEMY
1944-1948

CONTENTS

	PAGE
I. <i>Officers and Committees for 1947-1948; Lists of Members; Statutes</i>	i-xxvii
II. <i>The Compression of Twenty-one Halogen Compounds and Eleven Other Simple Substances to 100,000 kg/cm². P. W. BRIDGMAN</i>	1
III. <i>The Compression of Sixty-one Solid Substances to 25,000 kg/cm², Determined by a New Rapid Method. P. W. BRIDGMAN</i>	9
IV. <i>Lower Permian Insects from Oklahoma. Part 1. Introduction and the Orders Megasecoptera, Protodonata, and Odonata. F. M. CARPENTER</i>	25
V. <i>The Compression of 39 Substances to 100,000 kg/cm². P. W. BRIDGMAN</i>	55
VI. <i>Rough Compressions of 177 Substances to 40,000 kg/cm². P. W. BRIDGMAN</i>	71
VII. <i>The Linear Compression of Various Single Crystals to 30,000 kg/cm². P. W. BRIDGMAN</i>	89
VIII. <i>The Scattering of High Velocity Neutral Particles. I. I. AMDUR, C. F. GLICK AND H. PEARLMAN</i>	101
IX. <i>Officers and Committees for 1948-1949; Records of Meetings, October, 1944 to May, 1948</i>	120

American Academy of Arts and Sciences

OFFICERS AND COMMITTEES FOR 1947-1948

PRESIDENT

HOWARD MUMFORD JONES

VICE-PRESIDENTS

Class I

ROLAND G. D. RICHARDSON

Class II

IRVING W. BAILEY

Class III

ERWIN N. GRISWOLD

Class IV

DONALD SCOTT

CORRESPONDING SECRETARY

JOHN W. M. BUNKER

RECORDING SECRETARY

ISADORE AMDUR

TREASURER

HORACE S. FORD

LIBRARIAN

FREDERICK H. PRATT

EDITOR

TAYLOR STARCK

EXECUTIVE OFFICER

RALPH W. BURHOE

COUNCILLORS

Class I

GUSTAVUS J. ESSELEN

JOHN H. VAN VLECK

PHILIP FRANKLIN

JOSEPH H. KEENAN

Terms expire 1948

Terms expire 1949

Terms expire 1950

Terms expire 1951

Class II

CHESTER S. KEEFER

CHARLES H. BLAKE

FREDERICK K. MORRIS

PAUL C. MANGELSDORF

Class III

LAURENCE L. WINSHIP

RALPH E. FREEMAN

CHARLES E. WYZANSKI, JR.

HARVEY H. BUNDY

Terms expire 1948

Terms expire 1949

Terms expire 1950

Terms expire 1951

Class IV

WARREN O. AULT

HARRY A. WOLFSON

JOHN G. BEEBE-CENTER

WILLIAM G. CONSTABLE

STANDING COMMITTEES

The Committee on Finance

HORACE S. FORD, *Chairman, ex officio*

RALPH E. FREEMAN

JEROME C. HUNSAKER

HENRY P. KENDALL

HENRY L. SHATTUCK

The Permanent Science Fund Committee

JOHN W. M. BUNKER, *Chairman*

ROGER ADAMS

KIRK BRYAN

A. BAIRD HASTINGS

EDWARD L. MORELAND

JULIUS A. STRATTON

PAYSON S. WILD, JR.

The Rumford Committee

HARLOW SHAPLEY, *Chairman*

PERCY W. BRIDGMAN

ARTHUR C. HARDY

GEORGE R. HARRISON

JOSEPH H. KEENAN

EDWIN H. LAND

FRANCIS O. SCHMITT

The Cyrus Moors Warren Committee

FREDERICK G. KEYES, *Chairman*

LOUIS F. FIESER

GRINNELL JONES

CHARLES A. KRAUS

KENNETH L. MARK

AVERY A. MORTON

WALTER C. SCHUMB

The Committee on Publication

TAYLOR STARCK, *Chairman, ex officio*

ERNEST H. HUNTRESS, *of Class I*

KENNETH V. THIMANN, *of Class II*

T. NORTH WHITEHEAD, *of Class III*

KENNETH B. MURDOCK, *of Class IV*

The Committee on the Library

FREDERICK H. PRATT, *Chairman, ex officio*

RAYMOND C. ARCHIBALD, *of Class I*

FRANCIS N. BALCH, *of Class III*

CHARLES A. WEATHERBY, *of Class II*

HENRY B. WASHBURN, *of Class IV*

The House Committee

CHARLES M. SPOFFORD, *Chairman*

CHESTER M. ALTER

H. ADDINGTON BRUCE

JOHN B. WILBUR

The Committee on Meetings

HOWARD M. JONES, *Chairman, ex officio*

ISADORE AMDUR, *ex officio*

BART J. BOK

DOUGLASS V. BROWN

ARTHUR CLAY COPE

HENRY B. PHILLIPS

The Auditing Committee

THOMAS H. SANDERS

DONALD S. TUCKER

The Amory Prize Committee

EDWIN B. WILSON, *Chairman*

WILLIAM B. CASTLE

GREGORY PINCUS

GEORGE B. WISLOCKI

ROY G. HOSKINS

GEORGE W. THORN

S. BURT WOLBACH

INTERIM SPECIAL COMMITTEE ON MEMBERSHIP

HOWARD M. JONES, *Chairman, ex officio*

Class I

J. LAWRENCE ONCLEY

GEORGE SCATCHARD

Class II

CHARLES A. JANEWAY

RALPH H. WETMORE

Class III

ROBERT G. CALDWELL

JAMES R. KILLIAN, JR.

Class IV

CURT J. DUCASSE

W. FREEMAN TWADDELL

LIST

OF THE

FELLOWS AND FOREIGN HONORARY MEMBERS

(Corrected to January 1, 1948)

FELLOWS—771

(Number limited to one thousand)

The year of election is indicated in the left margin, the century being omitted; thus 21 means 1921, 92 means 1892. When a Fellow resigned and was re-elected, the year of re-election is indicated in the ordinary way, the year of election is enclosed in square brackets. The year of election of an Associate, now a Fellow, is indicated by round brackets.

CLASS I—MATHEMATICAL AND PHYSICAL SCIENCES—216

SECTION I—Mathematics and Astronomy—48

- 21 Charles Greeley Abbot Washington, D. C.
- 32 Clarence Raymond Adams Providence, R. I.
- 22 Walter Sydney Adams Pasadena, Cal.
- 12 George Russell Agassiz Dedham
- 47 Howard Hathaway Aiken Cambridge
- 17 Raymond Clare Archibald Providence, R. I.
- 46 James Gilbert Baker Waban
- 46 John Landes Barnes Pacific Palisades, Calif.
- 32 Albert Arnold Bennett Providence, R. I.
- 45 Garrett Birkhoff Cambridge
- 35 Gilbert Ames Bliss Chicago, Ill.
- 39 Bart Jan Bok Lexington
- 46 Subrahmanyan Chandrasekhar Williams Bay, Wis.
- 13 Julian Lowell Coolidge Cambridge
- 15 Leonard Eugene Dickson Chicago, Ill.
- 33 Jesse Douglas Brooklyn, N. Y.
- 38 John Charles Duncan Wellesley
- 34 Griffith Conrad Evans Berkeley, Cal.
- 30 Philip Franklin Belmont
- 32 Einar Hille New Haven, Conn.
- 13 Edward Vermilye Huntington Cambridge
- 38 E[lv]in Morton Jellinek New Haven, Conn.
- 15 Carl Otto Lampland Flagstaff, Ariz.
- 45 Norman Levinson Belmont
- 25 Willem Jacob Luyten Minneapolis, Minn.
- 44 Saunders MacLane Chicago, Ill.
- 34 Donald Howard Menzel Cambridge
- 19 George Abram Miller Urbana, Ill.
- 23 Samuel Alfred Mitchell University, Va.
- 29 Marston Morse Princeton, N. J.
- 19 Forest Ray Moulton Washington, D. C.
- 44 John von Neumann Princeton, N. J.
- 43 Cecilia Payne-Gaposchkin Lexington
- 18 Henry Bayard Phillips Lincoln
- 96 Charles Lane Poor New York, N. Y.

- 14 Roland George Dwight Richardson,
Providence, R. I.
- 02 Henry Norris Russell Cambridge
- 20 Harlow Shapley Cambridge
- 09 Vesto Melvin Slipher Flagstaff, Ariz.
- 19 Virgil Snyder Ithaca, N. Y.
- 21 Joel Stebbins Madison, Wis.
- 27 Harlan True Stetson Needham
- 30 Dirk Jan Struik Belmont
- 42 Otto Struve Williams Bay, Wis.
- 23 Oswald Veblen Princeton, N. J.
- 29 Joseph Leonard Walsh Cambridge
- 41 Fred Lawrence Whipple Cambridge
- 32 David Vernon Widder Belmont

CLASS I, SECTION II—Physics—62

- 28 Adelbert Ames, Jr. Hanover, N. H.
- 37 Kenneth Tompkins Bainbridge Cambridge
- 21 Samuel Jackson Barnett Pasadena, Cal.
- 42 Francis Birch Cambridge
- 12 Percy Williams Bridgman Cambridge
- 39 Lyman James Briggs Washington, D. C.
- 26 Walter Guyton Cady Middletown, Conn.
- 03 George Ashley Campbell Upper Montclair, N. J.
- 21 Leslie Lyle Campbell Lexington, Va.
- 16 Emory Leon Chaffee Belmont
- 28 Arthur Holly Compton St. Louis, Mo.
- 31 Karl Taylor Compton Cambridge
- 12 Daniel Frost Comstock Lincoln
- 47 Edward Uhler Condon Washington, D. C.
- 15 William David Coolidge Schenectady, N. Y.
- 34 Franzo Hazlett Crawford Williamstown
- 13 Henry Crew Evanston, Ill.
- 11 Harvey Nathaniel Davis Hoboken, N. J.
- 29 Clinton Joseph Davisson New York, N. Y.
- 12 Arthur Louis Day Bethesda, Md.
- 46 Lee Alvin Du Bridge Pasadena, Cal.
- 01 Alexander Wilmer Duff Worcester

- | | | | |
|--------------------------------------|-------------------|------------------------------------|--------------------|
| 45 Robley Dunglison Evans..... | Belmont | 40 William Lloyd Evans..... | Columbus, O. |
| 09 Arthur Woolsey Ewell..... | Worcester | 33 Louis Frederick Fieser..... | Belmont |
| 39 Harry Edward Farnsworth..... | Providence, R. I. | 15 George Shannon Forbes..... | Cambridge |
| 43 Philipp Frank..... | Cambridge | 35 Louis Harris..... | Belmont |
| 97 Harry Manley Goodwin..... | Brookline | 36 Albert Baird Hastings..... | Brookline |
| 29 Arthur Cobb Hardy..... | Wellesley | 38 Robert Casad Hockett..... | Concord |
| 31 George Russell Harrison..... | Belmont | 36 Ernest Hamlin Huntress..... | Melrose Highlands |
| 14 John Charles Hubbard..... | Washington, D. C. | 19 Frederick George Keyes..... | Cambridge |
| 17 Gordon Ferrie Hull..... | Hanover, N. H. | 33 George Bogdan Kistiakowsky..... | Cambridge |
| 40 Frederick Vinton Hunt..... | Belmont | 15 Charles August Kraus..... | Providence, R. I. |
| 22 Edwin Crawford Kemble..... | Cambridge | 14 Arthur Becket Lamb..... | Brookline |
| 44 Ronold Wyeth Percival King..... | Winchester | 18 Irving Langmuir..... | Schenectady, N. Y. |
| 43 Edwin Herbert Land..... | Cambridge | 15 Warren Kendall Lewis..... | Newton |
| 37 Ernest Orlando Lawrence..... | Berkeley, Cal. | 23 Duncan Arthur MacInnes..... | New York, N. Y. |
| 31 Robert Bruce Lindsay..... | Providence, R. I. | 32 Kenneth Lamartine Mark..... | Boston |
| 01 Theodore Lyman..... | Brookline | 41 Charles Edward Kenneth Mees... | Rochester, N. Y. |
| 34 Louis Williams McKeehan..... | Washington, D. C. | 35 Nicholas Athanasius Milas..... | Belmont |
| 14 Ernest George Merritt..... | Ithaca, N. Y. | 36 Avery Adrian Morton..... | Watertown |
| 14 Robert Andrews Millikan..... | Pasadena, Cal. | 19 Edward Mueller..... | Cambridge |
| 34 Harry Rowe Minno..... | Lexington | 31 William Albert Noyes, Jr..... | Rochester, N. Y. |
| 34 Philip McCord Morse..... | Bayport, N. Y. | 45 John Lawrence Oncley..... | Watertown |
| 31 Otto Oldenberg..... | Cambridge | 44 Linus Carl Pauling..... | Pasadena, Cal. |
| 40 J. Robert Oppenheimer..... | Princeton, N. J. | 39 Clifford Burrough Purves..... | Montreal, Can. |
| 34 Leigh Page..... | New Haven, Conn. | 14 Martin André Rosanoff..... | Mt. Lebanon, Pa. |
| 07 George Washington Pierce..... | Cambridge | 28 George Scatchard..... | Cambridge |
| 41 Isidor Isaac Rabi..... | New York, N. Y. | 32 Walter Cecil Schumb..... | East Milton |
| 27 John Clarke Slater..... | Cambridge | 15 Miles Standish Sherrill..... | Cambridge |
| 37 George Walter Stewart..... | Iowa City, Ia. | 20 Harry Monmouth Smith..... | Brookline |
| 43 Donald Charles Stockbarger..... | Belmont | 34 Leighton Bruerton Smith..... | Beverly |
| 46 Julius Adams Stratton..... | Belmont | 47 Clark Conkling Stephenson..... | Cambridge |
| 37 Jabez Curry Street..... | Belmont | 46 Walter Hugo Stockmayer..... | Weston |
| 12 Maurice deKay Thompson..... | Newark, N. J. | 43 Hugh Stott Taylor..... | Princeton, N. J. |
| 28 Manuel Sandoval Vallarta..... | Mexico, D. F. | 22 Richard Chace Tolman..... | Pasadena, Cal. |
| 35 Robert Jemison Van de Graaff..... | Belmont | 38 Harold Clayton Urey..... | Chicago, Ill. |
| 34 John Hasbrouck Van Vleck..... | Cambridge | 41 Harry Boyer Weiser..... | Houston, Tex. |
| 35 Bertram Eugene Warren..... | Arlington | 11 Willis Rodney Whitney..... | Schenectady, N. Y. |
| 18 David Locke Webster..... | Palo Alto, Cal. | 19 Robert Seaton Williams..... | Belmont |
| 11 Edwin Bidwell Wilson..... | Brookline | 44 Edgar Bright Wilson, Jr..... | Cambridge |
| 13 Robert Williams Wood..... | Baltimore, Md. | 41 Ralph Chillingworth Young..... | Arlington |
| 17 John Zeleny..... | New Haven, Conn. | | |

CLASS I, SECTION III—Chemistry—57

- | | |
|-----------------------------------|-------------------|
| 26 Roger Adams..... | Urbana, Ill. |
| 44 Isadore Amdur..... | Cambridge |
| 45 Eric Glendinning Ball..... | Newton Highlands |
| 13 Wilder Dwight Bancroft..... | Ithaca, N. Y. |
| 46 Paul Doughty Bartlett..... | Weston |
| 07 Gregory Paul Baxter..... | Cambridge |
| 29 James Alexander Beattie..... | Belmont |
| 19 Arthur Alphonzo Blanchard..... | Brookline |
| 14 Marston Taylor Bogert..... | New York, N. Y. |
| 36 Harold Simmons Booth..... | Cleveland, O. |
| 38 Emile Monnin Chamot..... | Ithaca, N. Y. |
| 42 Samuel Cornette Collins..... | Belmont |
| 24 James Bryant Conant..... | Cambridge |
| 45 Arthur Clay Cope..... | Belmont |
| 47 Paul Clifford Cross..... | Providence, R. I. |
| 23 Tenney Lombard Davis..... | Norwell |
| 37 John Tileston Edsall..... | Dedham |
| 37 Gustavus John Esselen..... | Swampscott |

CLASS I, SECTION IV—Technology and Engineering—49

- | | |
|--------------------------------------|-------------------|
| 06 Comfort Avery Adams..... | Philadelphia, Pa. |
| 42 Wilmer Lanier Barrow..... | Concord |
| 33 Harold Kilbrith Barrows..... | Winchester |
| 31 Charles Harold Berry..... | Belmont |
| 41 Edward Lindley Bowles..... | Wellesley |
| 25 Vannevar Bush..... | Washington, D. C. |
| 45 Hardy Cross..... | New Haven, Conn. |
| 34 Otto Gustav Colbiornsen Dahl..... | Boston |
| 34 Chester Laurens Dawes..... | Cambridge |
| 34 Jacob Pieter Den Hartog..... | Wellesley Hills |
| 43 Bradley Dewey..... | Cambridge |
| 20 Theodore Harwood Dillon..... | Washington, D. C. |
| 41 Charles Stark Draper..... | Newton |
| 22 Gano Dunn..... | New York, N. Y. |
| 21 William Frederick Durand..... | Palo Alto, Cal. |
| 46 Howard Wilson Emmons..... | Sudbury |
| 27 Gordon Maskew Fair..... | Cambridge |
| 32 Glennon Gilboy..... | Lincoln |
| 32 Albert Haertlein..... | Watertown |

40 Harold Locke Hazen Belmont
 44 Arthur Robert von Hippel Weston
 36 Murray Philip Horwood Cambridge
 34 Jerome Clarke Hunsaker Boston
 23 James Robertson Jack Watertown
 11 Dugald Caleb Jackson Cambridge
 30 Frank Baldwin Jewett Short Hills, N. J.
 01 Lewis Jerome Johnson Cambridge
 37 Joseph Henry Keenan Belmont
 32 Ralph Restieaux Lawrence Belmont
 23 William Henry Lawrence Jamaica Plain
 38 John Moyes Lessells Brookline
 47 Charles Winters MacGregor Belmont
 12 Lionel Simeon Marks Cambridge
 44 Richard von Mises Cambridge
 34 Edward Leyburn Moreland Wellesley
 20 Frederick Law Olmsted Elkton, Md.
 28 Langdon Pearse Chicago, Ill.
 13 Harold Pender Philadelphia, Pa.
 30 Greenleaf Whittier Pickard Newton Center
 41 Reinhold Rüdenberg Belmont
 39 C. Richard Soderberg Weston
 14 Charles Milton Spofford Boston
 45 Frederick Emmons Terman Palo Alto, Cal.
 [28] 44 Karl Terzaghi Winchester
 23 Edward Pearson Warner Montreal, Canada
 37 Harald Malcolm Westergaard Belmont
 45 John Benson Wilbur Belmont
 40 John Wulff Cambridge
 41 Vladimir Kosma Zworykin Princeton, N. J.

CLASS II—NATURAL AND PHYSIOLOGICAL
 SCIENCES—210

SECTION I—*Geology, Mineralogy, and Physics of the
 Globe*—42

15 Wallace Walter Atwood Worcester
 41 Alan Mara Bateman New Haven, Conn.
 46 Roland Frank Beers Lincoln
 38 Marland Pratt Billings Wellesley
 21 Norman Levi Bowen Chicago, Ill.
 16 Isaiah Bowman Baltimore, Md.
 33 Charles Franklin Brooks Milton
 29 Kirk Bryan Cambridge
 45 Martin Julian Buerger Lincoln
 33 Frank Morton Carpenter Lexington
 34 Sterling Price Fergusson Milton
 42 Russell Gibson Belmont
 14 Louis Caryl Graton Cambridge
 17 Herbert Ernest Gregory Honolulu, T. H.
 21 William Jackson Humphreys Washington, D. C.
 46 Cornelius Searle Hurlbut, Jr. Belmont
 44 Columbus O'Donnell Iselin Woods Hole
 95 Robert Tracy Jackson Peterborough, N. H.
 02 Thomas Augustus Jaggard Honolulu, T. H.
 10 Alfred Church Lane Cambridge
 25 Esper Signius Larsen, Jr. Belmont
 15 Andrew Cowper Lawson Berkeley, Cal.
 16 Charles Kenneth Leith Madison, Wis.
 31 George Francis McEwen La Jolla, Cal.
 27 Donald Hamilton McLaughlin San Francisco, Cal.

25 Kirtley Fletcher Mather Newton Center
 35 Warren Judson Mead Belmont
 17 William John Miller Los Angeles, Cal.
 32 Frederick Kuhne Morris Cambridge
 34 Walter Harry Newhouse Chicago, Ill.
 22 Austin Flint Rogers Palo Alto, Cal.
 34 Carl-Gustaf Arvid Rossby Chicago, Ill.
 19 Waldemar Theodore Schaller Washington, D. C.
 45 Henry Crosby Stetson Belmont
 41 Chester Stock Pasadena, Cal.
 44 Harald Ulrik Sverdrup La Jolla, Cal.
 17 Thomas Wayland Vaughan Washington, D. C.
 08 Charles Hyde Warren New Haven, Conn.
 14 Herbert Percy Whitlock New York, N. Y.
 35 Derwent Stainthorpe Whittlesey Cambridge
 15 Bailey Willis Palo Alto, Cal.
 15 Frederick Eugene Wright Washington, D. C.

CLASS II, SECTION II—*Botany*—36

30 LeRoy Abrams Palo Alto, Cal.
 11 Oakes Ames North Easton
 34 Edgar Anderson St. Louis, Mo.
 15 Irving Widmer Bailey Cambridge
 00 Liberty Hyde Bailey Ithaca, N. Y.
 40 Albert Francis Blakeslee Northampton
 98 Douglas Houghton Campbell Palo Alto, Cal.
 46 Ralph Erskine Cleland Bloomington, Ind.
 16 Bradley Moore Davis Ann Arbor, Mich.
 35 Bernard Ogilvie Dodge New York, N. Y.
 41 Arthur Johnson Eames Ithaca, N. Y.
 21 Rollins Adams Emerson Ithaca, N. Y.
 12 Alexander William Evans New Haven, Conn.
 00 Merritt Lyndon Fernald Cambridge
 44 Paul Rupert Gast Petersham
 45 Dennis Robert Hoagland Berkeley, Cal.
 98 John George Jack East Walpole
 27 Ivan Murray Johnston Brookline
 34 Donald Forsha Jones New Haven, Conn.
 14 Burton Edward Livingston Riderwood, Md.
 40 Paul Christoph Mangelsdorf Newtonville
 42 William Ralph Maxon Washington, D. C.
 21 Elmer Drew Merrill Jamaica Plain
 10 Winthrop John Vanleuven Osterhout,
 New York, N. Y.
 27 George James Peirce Palo Alto, Cal.
 44 Hugh Miller Raup Jamaica Plain
 14 Alfred Rehder Jamaica Plain
 34 Edmund Ware Sinnott New Haven, Conn.
 44 Albert Charles Smith Jamaica Plain
 34 Gilbert Morgan Smith Palo Alto, Cal.
 45 Herman Augustus Spoehr Palo Alto, Cal.
 23 Elvin Charles Stakman St. Paul, Minn.
 38 Kenneth Vivian Thimann Cambridge
 31 Charles Alfred Weatherby Cambridge
 22 William Henry Weston, Jr. Winchester
 32 Ralph Hartley Wetmore Cambridge

CLASS II, SECTION III—*Zoology and Physiology*—65

22 Nathan Banks Holliston
 33 Philip Bard Baltimore, Md.

- 46 George Wells Beadle.....Pasadena, Cal.
 09 Francis Gano Benedict.....Machiasport, Me.
 11 Henry Bryant Bigelow.....Concord
 14 Robert Payne Bigelow.....Brookline
 35 Charles Henry Blake.....Lincoln
 20 William T. Bovie.....Fairfield, Me.
 24 Edward Allen Boyden.....Minneapolis, Minn.
 16 John Lewis Bremer.....Boston
 28 John Wymond Miller Bunker.....Belmont
 22 Thorne Martin Carpenter.....Foxboro
 00 William Ernest Castle.....Berkeley, Cal.
 29 Lemuel Roscoe Cleveland.....Jamaica Plain
 26 Edwin Joseph Cohn.....Cambridge
 14 Edwin Grant Conklin.....Princeton, N. J.
 23 Manton Copeland.....Brunswick, Me.
 27 William John Crozier.....Belmont
 17 Joseph Augustine Cushman.....Sharon
 29 Hallowell Davis.....St. Louis, Mo.
 33 Alden Benjamin Dawson.....Belmont
 25 Samuel Randall Detwiler.....New York, N. Y.
 43 David Bruce Dill.....Edgewood Arsenal, Md.
 25 Herbert McLean Evans.....Berkeley, Cal.
 34 Cyrus Hartwell Fiske.....Lexington
 15 Alexander Forbes.....Milton
 34 John Farquhar Fulton.....New Haven, Conn.
 47 Arnold Lucius Gesell.....New Haven, Conn.
 31 William King Gregory.....New York, N. Y.
 36 Frederick Lee Hisaw.....Belmont
 29 Leigh Hoadley.....Cambridge
 34 Hudson Hoagland.....Worcester
 24 Samuel Jackson Holmes.....Berkeley, Cal.
 28 Roy Graham Hoskins.....Waban
 13 Leland Ossian Howard.....Washington, D. C.
 44 Eugene Markley Landis.....Brookline
 16 Frederic Thomas Lewis.....Waban
 14 Ralph Stayner Lillie.....Chicago, Ill.
 45 John Robert Loofbourow.....Cambridge
 17 Richard Swann Lull.....New Haven, Conn.
 43 Brenton Reid Lutz.....Melrose
 27 Axel Leonard Melander.....Riverside, Cal.
 35 Karl Friedrich Meyer.....San Francisco, Cal.
 21 Gerrit Smith Miller.....Washington, D. C.
 42 Hermann Joseph Muller.....Bloomington, Ind.
 95 George Howard Parker.....Cambridge
 46 James Lee Peters.....Harvard
 21 Henry Augustus Pilsbry.....Philadelphia, Pa.
 39 Gregory Pincus.....Worcester
 27 Frederick Haven Pratt.....Wellesley Hills
 09 Herbert Wilbur Rand.....Cambridge
 32 David Rapport.....Cambridge
 23 Alfred Clarence Redfield.....Woods Hole
 34 Alfred Newton Richards.....Bryn Mawr, Pa.
 34 Oscar Riddle.....Cold Spring Harbor, N. Y.
 46 Kenneth David Roeder.....Concord
 37 Alfred Sherwood Romer.....Cambridge
 25 Alexander Grant Ruthven.....Ann Arbor, Mich.
 41 Francis Otto Schmitt.....Belmont
 45 John Henry Welsh, Jr.....Cambridge
 15 Arthur Wisswald Weyse.....Woburn
 38 George Bernays Wislocki.....Milton
- 33 Jeffries Wyman, Jr.....Chestnut Hill
 45 Leland Clifton Wyman.....Jamaica Plain
 15 Robert Mearns Yerkes.....New Haven, Conn.
- CLASS II, SECTION IV—*Medicine and Surgery*—67
- 41 Fuller Albright.....Brookline
 47 Arthur Wilburn Allen.....Brookline
 32 Joseph Charles Aub.....Belmont
 36 Oswald Theodore Avery.....New York, N. Y.
 29 James Bourne Ayer.....Milton
 (28) 32 Franklin Greene Balch.....Boston
 41 Walter Bauer.....Waban
 47 David Lawrence Belding.....Boston
 31 George Blumer.....San Marino, Cal.
 43 Arlie Vernon Bock.....Cambridge
 36 Charles Sidney Burwell.....Brookline
 31 William Bosworth Castle.....Brookline
 30 David Cheever.....Boston
 13 Henry Asbury Christian.....Brookline
 42 William Irving Clark.....Worcester
 21 Rufus Cole.....Mount Kisco, N. Y.
 31 Eugene Floyd DuBois.....New York, N. Y.
 46 John Franklin Enders.....Boston
 45 James Morison Faulkner.....Brookline
 44 Maxwell Finland.....Squantum
 33 Reginald Fitz.....Brookline
 27 James Lawder Gamble.....Brookline
 22 Joseph Lincoln Goodale.....Ipswich
 45 Thomas Hale Ham.....Brookline
 21 Ross Granville Harrison.....New Haven, Conn.
 47 Sanford Burton Hooker.....West Roxbury
 27 Percy Rogers Howe.....Belmont
 33 Edgar Erskine Hume.....Frankfort, Ky.
 34 Henry Jackson, Jr.....Chestnut Hill
 46 Charles Alderson Janeway.....Weston
 12 Elliott Proctor Joslin.....Boston
 43 Chester Scott Keefer.....Brookline
 23 Roger Irving Lee.....Brookline
 42 Samuel Albert Levine.....Newton Center
 29 Edwin Allen Locke.....Wilton, N. H.
 28 Warfield Theobald Longcope.....Baltimore, Md.
 32 Fred Bates Lund.....Newton Center
 40 William de Berniere MacNider.....Chapel Hill, N. C.
 44 William Malamud.....Worcester
 34 Leroy Matthew Simpson Miner.....Newtonville
 26 George Richards Minot.....Brookline
 28 William Lorenzo Moss.....Athens, Ga.
 28 John Howard Mueller.....West Roxbury
 25 Robert Bayley Osgood.....Boston
 37 Walter Walker Palmer.....New York, N. Y.
 27 Joseph Hersey Pratt.....Brookline
 35 Tracy Jackson Putnam.....New York, N. Y.
 34 William Carter Quinby.....Brookline
 47 Francis Minot Rackemann.....Boston
 34 Arthur Hiler Ruggles.....Providence, R. I.
 39 Frederick Fuller Russell.....Brookline
 39 William Thomas Salter.....New Haven, Conn.
 33 George Cheever Shattuck.....Brookline
 47 James Stevens Simmons.....Boston
 47 Richard Mason Smith.....Boston

- 30 Torald Hermann Sollmann.....Cleveland, O.
 47 Merrill Clary Sosman.....Chestnut Hill
 14 Richard Pearson Strong.....Boston
 30 Fritz Bradley Talbot.....Brookline
 46 Siegfried Josef Thannhauser.....Brookline
 44 George Widmer Thorn.....Cambridge
 14 Ernest Edward Tyzzer.....Wakefield
 14 Frederick Herman Verhoeff.....Brookline
 47 Shields Warren.....West Newton
 27 Joseph Treloar Wearn.....Cleveland, O.
 40 Paul Dudley White.....Brookline
 12 Simeon Burt Wolbach.....South Sudbury

CLASS III—THE SOCIAL ARTS—171

SECTION I—*Jurisprudence*—37

- (24) 32 Francis Noyes Balch.....Jamaica Plain
 38 Henry Moore Bates.....Ann Arbor, Mich.
 36 Stoughton Bell.....Cambridge
 33 Harry Augustus Bigelow.....Chicago, Ill.
 36 Claude Raymond Branch.....Providence, R. I.
 33 John Dickinson.....Philadelphia, Pa.
 38 Robert Gray Dodge.....Boston
 31 Fred Tarbell Field.....Newton
 40 Lon Louvois Fuller.....Cambridge
 39 Herbert Funk Goodrich.....Philadelphia, Pa.
 33 Theodore Francis Green.....Providence, R. I.
 38 Frank Washburn Grinnell.....Boston
 41 Erwin Nathaniel Griswold.....Belmont
 39 John Loomer Hall.....Boston
 39 Augustus Noble Hand.....New York, N. Y.
 33 Learned Hand.....New York, N. Y.
 39 Albert James Harno.....Urbana, Ill.
 47 Mark DeWolfe Howe.....Cambridge
 18 Charles Evans Hughes.....Washington, D. C.
 38 Melvin Maynard Johnson.....Brookline
 38 James McCauley Landis.....Washington, D. C.
 32 Sayre Macneil.....Pasadena, Cal.
 32 Calvert Magruder.....Cambridge
 31 William DeWitt Mitchell.....New York, N. Y.
 31 Edmund Morris Morgan.....Arlington
 47 John Lord O'Brian.....Washington, D. C.
 36 Henry Parkman, Jr.....Boston
 39 Robert Porter Patterson.....New York, N. Y.
 01 George Wharton Pepper.....Philadelphia, Pa.
 11 Roscoe Pound.....Watertown
 36 Stanley Elroy Qua.....Lowell
 32 Francis Bowes Sayre.....Washington, D. C.
 21 Austin Wakeman Scott.....Cambridge
 36 Sidney Post Simpson.....Cambridge
 39 Thomas Walter Swan.....New York, N. Y.
 32 Edward Sampson Thurston.....San Francisco, Cal.
 43 Charles Edward Wyzanski, Jr.....Cambridge

CLASS III, SECTION II—*Government, International
Law, and Diplomacy*—30

- 36 Howard Landis Bevis.....Columbus, O.
 33 Edwin Montefiore Borchard.....New Haven, Conn.
 46 Harvey Hollister Bundy.....Boston
 40 Robert Granville Caldwell.....Belmont
 32 William Richards Castle, Jr.....Washington, D. C.

- 32 Joseph Perkins Chamberlain.....New York, N. Y.
 33 Robert Treat Crane.....New York, N. Y.
 35 Tyler Dennett.....Hague, N. Y.
 46 John Sloan Dickey.....Hanover, N. H.
 27 William Cameron Forbes.....Norwood
 44 Carl Joachim Friedrich.....Concord
 34 Edgar Stephenson Furniss.....New Haven, Conn.
 32 Joseph Clark Grew.....Washington, D. C.
 35 Charles Grove Haines.....Los Angeles, Cal.
 41 Hajo Holborn.....Hamden, Conn.
 27 Arthur Norman Holcombe.....Cambridge
 32 Philip Carryl Jessup.....New York, N. Y.
 32 Charles Edward Merriam.....Chicago, Ill.
 13 William Bennett Munro.....Pasadena, Cal.
 47 William Phillips.....North Beverly
 41 Gaetano Salvemini.....Cambridge
 46 Robert Burgess Stewart.....Winchester
 40 Thomas Head Thomas.....Cambridge
 44 Sarah Wambaugh.....Cambridge
 47 Sumner Welles.....Oxon Hill, Md.
 43 Payson Sibley Wild, Jr.....Cambridge
 32 William Franklin Willoughby.....Washington, D. C.
 14 George Grafton Wilson.....Grafton, Vt.
 27 Quincy Wright.....Chicago, Ill.
 33 Henry Aaron Yeomans.....Harvard

CLASS III, SECTION III—*Economics and Sociology*—58

- 36 James Waterhouse Angell.....New York, N. Y.
 47 George Pierce Baker.....Boston
 36 James Cummings Bonbright.....New York, N. Y.
 43 Augusta Fox Bronner (Mrs. William Healy) Boston
 44 Douglass Vincent Brown.....Brookline
 46 Theodore Henry Brown.....Cambridge
 33 Harold Hitchings Burbank.....Cambridge
 34 John Maurice Clark.....Westport, Conn.
 28 Arthur Harrison Cole.....Cambridge
 21 Clive Day.....New Haven, Conn.
 32 Arthur Stone Dewing.....Newton
 41 Carl Rupp Doering.....Cambridge
 32 Wallace Brett Donham.....Cambridge
 36 Fred Rogers Fairchild.....Hamden, Conn.
 36 Frank Albert Fetter.....Princeton, N. J.
 34 Ralph Evans Freeman.....Cambridge
 33 Sheldon Glueck.....Cambridge
 34 Robert Murray Haig.....New York, N. Y.
 41 Earl Jefferson Hamilton.....Evanston, Ill.
 45 Seymour Edwin Harris.....West Acton
 32 Henry Wyman Holmes.....Cambridge
 34 Frank Hyneman Knight.....Chicago, Ill.
 36 Roswell Cheney McCrea.....Augusta, Ga.
 34 Robert Morison MacIver.....New York, N. Y.
 32 Walter Wallace McLaren.....Williamstown
 45 William Rupert MacLaurin.....Cambridge
 36 Malcolm Perrine McNair.....Cambridge
 32 Leon Carroll Marshall.....Chevy Chase, Md.
 34 Richard Stockton Meriam.....South Lincoln
 34 Harry Alvin Millis.....Chicago, Ill.
 32 Frederick Cecil Mills.....New York, N. Y.
 31 Wesley Clair Mitchell.....New York, N. Y.
 34 Arthur Eli Monroe.....Cambridge

- | | | |
|----|-----------------------------------|-------------------|
| 34 | Edwin Griswold Nourse | Washington, D. C. |
| 32 | William Fielding Ogburn | Chicago, Ill. |
| 45 | Talcott Parsons | Belmont |
| 42 | William Andrew Paton | Ann Arbor, Mich. |
| 47 | Fritz Jules Roethlisberger | Cambridge |
| 37 | Clyde Orval Ruggles | Cambridge |
| 42 | Paul Anthony Samuelson | Belmont |
| 36 | Thomas Henry Sanders | Cambridge |
| 33 | Josef Alois Schumpeter | Cambridge |
| 43 | Benjamin Morris Selekman | Cambridge |
| 31 | Pitirim Alexandrovich Sorokin | Winchester |
| 41 | Francis Trow Spaulding | Albany, N. Y. |
| 31 | Oliver Mitchell Wentworth Sprague | Cambridge |
| 46 | Harold Walter Stoke | Baton Rouge, La. |
| 34 | Frederick John Teggart | Berkeley, Cal. |
| 37 | Harry Rudolph Tosdal | Belmont |
| 31 | Donald Skeeel Tucker | Belmont |
| 41 | Robert Ulich | Cambridge |
| 33 | Abbott Payson Usher | Salem |
| 34 | Jacob Viner | Princeton, N. J. |
| 38 | T[homas] North Whitehead | Cambridge |
| 32 | John Henry Williams | Cambridge |
| 36 | Joseph Henry Willits | New York, N. Y. |
| 34 | Leo Wolman | New York, N. Y. |
| 34 | Carle Clark Zimmerman | Winchester |

CLASS III, SECTION IV—*Administration and Affairs*—45

- (25) 32 Charles Francis Adams Concord
46 Chester M. Alter West Newton
39 Chester Irving Barnard Newark, N. J.
(25) 32 Charles Foster Batchelder,
Peterborough, N. H.
44 Adolf Augustus Berle, Jr. New York, N. Y.
45 Edwin Sharp Burdell New York, N. Y.
41 Godfrey Lowell Cabot Boston
47 Thomas Dudley Cabot Weston
47 William Henry Claflin, Jr. Belmont
43 Ada Louise Comstock (Mrs. Wallace Notestein),
New Haven, Conn.
42 Donald Kirk David Boston
38 Edmund Ezra Day Ithaca, N. Y.
32 Henry Sturgis Dennison Framingham
46 David Frank Edwards Cambridge
(28) 32 William Lusk Webster Field Milton
39 Ralph Edward Flanders Springfield, Vt.
38 Horace Sayford Ford Belmont
44 Raymond Blaine Fosdick New York, N. Y.
35 Jerome Davis Greene Cambridge
(28) 32 Edward Jackson Holmes Topsfield
44 Ernest Martin Hopkins Hanover, N. H.
34 Henry Plimpton Kendall Sharon
44 James Rhyne Killian, Jr. Wellesley Hills
32 Thomas William Lamont New York, N. Y.
39 Morris Evans Leeds Philadelphia, Pa.
34 Clarence Cook Little Bar Harbor, Me.
47 Ralph Lowell Westwood
36 Dumas Malone New York, N. Y.
42 Daniel L. Marsh Boston

45. Keyes DeWitt Metcalf. Belmont
45 Henry Allen Moe. New York, N. Y.
02 Herbert Putnam. Washington, D. C.
44 Beardsley Ruml. New York, N. Y.
34 Erwin Haskell Schell. Cambridge
38 Charles Seymour. New Haven, Conn.
35 Henry Lee Shattuck. Boston
37 Henry Southworth Shaw. Melrose
(28) 32 Payson Smith. Orono, Me.
46 Huntley Nowell Spaulding. Rochester, N. H.
33 Albert Warren Stearns. Billerica
(24) 32 Edwin Sibley Webster. Brookline
44 Charles Edward Wilson. New York, N. Y.
41 Laurence Leathe Winship. South Sudbury
(25) 32 Benjamin Loring Young. Weston
39 Owen D. Young. New York, N. Y.

CLASS IV—THE HUMANITIES—175

SECTION I—*Theology, Philosophy, and Psychology*—40

- 32 Michael Joseph Ahern..... Weston
32 James Rowland Angell..... Hamden, Conn.
33 John Gilbert Beebe-Center..... Swampscott
38 Julius Seelye Bixler..... Waterville, Me.
46 Brand Blanshard..... New Haven, Conn.
24 Edwin Garrigues Boring..... Cambridge
28 Edgar Sheffield Brightman..... Newton
31 Henry Addington Bruce..... Cambridge
32 Leonard Carmichael..... Tufts College
36 Robert Pierce Casey..... Providence, R. I.
33 Curt John Ducasse..... Providence, R. I.
43 Angus Dun..... Washington, D. C.
38 James Everett Frame..... Princeton, N. J.
37 Clarence Henry Graham..... New York, N. Y.
45 Edwin Ray Guthrie..... Seattle, Wash.
30 William Henry Paine Hatch..... Cambridge
32 William Healy..... Natick
35 Clark Leonard Hull..... New Haven, Conn.
28 Albert Cornelius Knudson..... Cambridge
32 Karl Spencer Lashley..... Orange Park, Fla.
29 Clarence Irving Lewis..... Lexington
42 Richard Peter McKeon..... Chicago, Ill.
35 Henry Alexander Murray, Jr..... Boston
47 Norman Burdett Nash..... Boston
32 Arthur Darby Nock..... Cambridge
28 Johnson O'Connor..... Boston
17 Charles Edwards Park..... Boston
33 Carroll Cornelius Pratt..... Princeton, N. J.
31 Henry Knox Sherrill..... New York, N. Y.
27 Willard Learoyd Sperry..... Cambridge
29 Russell Henry Stafford..... Hartford, Conn.
46 Stanley Smith Stevens..... Cambridge
45 Charles Lincoln Taylor, Jr..... Cambridge
34 Lewis Madison Terman..... Palo Alto, Cal.
34 Edward Lee Thorndike..... Montrose, N. Y.
37 Louis Leon Thurstone..... Chicago, Ill.
28 Henry Bradford Washburn..... Cambridge
17 John Broadus Watson..... New York, N. Y.
33 Frederic Lyman Wells..... Newton Highlands
35 Robert Sessions Woodworth..... New York, N. Y.

CLASS IV, SECTION II—*History, Archaeology, and
Anthropology*—35

- 41 Warren Ortman Ault Waban
28 James Phinney Baxter, 3d Williamstown
47 Ruth Fulton Benedict New York, N. Y.
27 Robert Pierpont Blake Cambridge
46 Clarence Saunders Brigham Worcester
39 Crane Brinton Cambridge
(25) 32 William Brooks Cabot Boston
42 Henry Joel Cadbury Cambridge
34 Clarence Gordon Campbell New York, N. Y.
43 Carleton Stevens Coon Cambridge
44 William Bell Dinsmoor New York, N. Y.
38 Claude Moore Fuess Andover
43 Hugh O'Neill Hencken Chestnut Hill
14 Bert Hodge Hill Athens, Greece
27 Earnest Albert Hooton Cambridge
33 Halford Lancaster Hoskins Washington, D. C.
47 Wilbur Kitchener Jordan Cambridge
44 Clyde Kay Maben Kluckhohn Cambridge
12 Alfred Louis Kroeber Berkeley, Cal.
44 Ambrose Lansing New York, N. Y.
32 Waldo Gifford Leland Washington, D. C.
41 William E. Lingelbach Philadelphia, Pa.
38 Stewart Mitchell Cambridge
15 Samuel Eliot Morison Boston
46 Otto Eduard Neugebauer Providence, R. I.
34 Robert Henry Pfeiffer Cambridge
34 David Moore Robinson Baltimore, Md.
23 Michael Ivanovich Rostovtzeff New Haven, Conn.
27 George Sarton Cambridge
38 Bernadotte Everly Schmitt Chicago, Ill.
36 Donald Scott Cambridge
26 Herbert Joseph Spinden Brooklyn, N. Y.
32 Charles Holt Taylor Cambridge
11 Alfred Marston Tozzer Cambridge
39 Henry Rouse Viets Brookline

CLASS IV, SECTION III—*Philology*—49

- 33 William Nickerson Bates Philadelphia, Pa.
35 Charles Henry Beeson Chicago, Ill.
33 Campbell Bonner Ann Arbor, Mich.
25 Robert Johnson Bonner Chicago, Ill.
41 Giuseppe Antonio Borgese Chicago, Ill.
21 Carl Darling Buck Chicago, Ill.
18 Edward Capps Princeton, N. J.
20 Walter Eugene Clark Cambridge
46 George Raleigh Coffman Chapel Hill, N. C.
32 Ronald Salmon Crane Chicago, Ill.
32 Morris William Croll Princeton, N. J.
44 Henry Grattan Doyle Washington, D. C.
20 Franklin Edgerton New Haven, Conn.
40 Serge Elisséeff Cambridge
14 Jeremiah Denis Mathias Ford Cambridge
16 Louis Herbert Gray New York, N. Y.
25 William Chase Greene Cambridge
13 Charles Burton Gulick Cambridge
34 Austin Morris Harmon New Haven, Conn.
31 Raymond Dexter Havens Baltimore, Md.
18 George Lincoln Hendrickson New Haven, Conn.

- 17 William Guild Howard Cambridge
40 Werner Wilhelm Jaeger Watertown
32 (Ralph) Hayward Keniston Ann Arbor, Mich.
34 Roland Grubb Kent Wynnewood, Pa.
33 Hans Kurath Ann Arbor, Mich.
39 Henry Carrington Lancaster Baltimore, Md.
33 Ivan Mortimer Linforth Berkeley, Cal.
44 Elias Avery Lowe Princeton, N. J.
35 Benjamin Dean Meritt Princeton, N. J.
28 William Albert Nitze Los Angeles, Cal.
32 George Rapall Noyes Berkeley, Cal.
33 Howard Rollin Patch Northampton
32 Arthur Stanley Pease Cambridge
11 Fred Norris Robinson Cambridge
38 Hyder Edward Rollins Cambridge
31 Robert Kilburn Root Princeton, N. J.
35 Henry Arthur Sanders Ann Arbor, Mich.
18 Rudolph Schevill Berkeley, Cal.
43 Jean Joseph Seznec Cambridge
45 George Wiley Sherburn Cambridge
45 Taylor Starck Cambridge
39 John Strong Perry Tatlock Berkeley, Cal.
32 William Thomson South Lincoln
11 Charles Cutler Torrey New Haven, Conn.
47 William Freeman Twaddell Providence, R. I.
30 Ernest Hatch Wilkins Newton Center
33 Harry Austryn Wolfson Cambridge
39 William Hoyt Worrell Ann Arbor, Mich.

CLASS IV, SECTION IV—*The Fine Arts and
Belles Lettres*—51

- 43 Leonard Bacon Peace Dale, R. I.
26 Frank Weston Benson Salem
32 (William) Welles Bosworth Locust Valley, N. Y.
47 Richard Burgin Brookline
42 John Nash Douglas Bush Cambridge
33 John Alden Carpenter Chicago, Ill.
45 Samuel Chamberlain Marblehead
32 Chalmers Dancy Clifton New York, N. Y.
32 Kenneth John Conant Cambridge
46 William George Constable Cambridge
34 Samuel Foster Damon Providence, R. I.
47 John Roderigo Dos Passos Provincetown
32 George Harold Edgell Cambridge
21 William Emerson Cambridge
30 John Erskine New York, N. Y.
18 Edward Waldo Forbes Cambridge
31 Robert Frost South Shaftsbury, Vt.
27 Wallace Goodrich Manchester
44 Walter Gropius Lincoln
31 Robert Silliman Hillyer Old Greenwich, Conn.
27 Charles Hopkinson Manchester
12 Mark Antony DeWolfe Howe Boston
38 Joseph Hudnut Cambridge
18 Archer Milton Huntington New York, N. Y.
45 William Alexander Jackson Cambridge
38 Howard Mumford Jones Cambridge
42 Otto Kinkeldey Ithaca, N. Y.
47 Milton Edward Lord Boston
21 Charles Donagh Maginnis Brookline

- 31 Paul Manship.....New York, N. Y.
 31 Daniel Gregory Mason.....New York, N. Y.
 31 Frank Jewett Mather....Washington Crossing, Pa.
 44 Charles Rufus Morey.....Princeton, N. J.
 47 Lewis Mumford.....Amenia, N. Y.
 31 Kenneth Ballard Murdock.....Boston
 (24) 32 Anthony John Philpott.....Arlington
 41 Walter Hamor Piston, Jr.....Belmont
 21 Chandler Rathfon Post.....Cambridge
 22 Paul Joseph Sachs.....Cambridge
 14 Ellery Sedgwick.....Boston
 19 Henry Dwight Sedgwick.....Dedham
 33 David Stanley Smith.....Woodbridge, Conn.
 39 Francis Henry Taylor.....New York, N. Y.
 43 Randall Thompson.....Princeton, N. J.
 44 Karl Viëtor.....Cambridge
 45 Martin Wagner.....Cambridge
 46 Edward Augustus Weeks, Jr.....Boston
 39 Karl Ephraim Weston.....Williamstown
 44 Herbert Eustis Winlock.....New York, N. Y.
 22 Charles Henry Conrad Wright.....Cambridge
 46 William Wilson Wurster.....Cambridge

FELLOWS EMERITI—33

CLASS I—MATHEMATICAL AND PHYSICAL SCIENCES—5

CLASS I, SECTION I—2

- 15 Frank Lauren Hitchcock.....Belmont
 [12] 44 Frederick Shenstone Woods....Newton Center

CLASS I, SECTION III—1

- 14 Samuel Cate Prescott.....Brookline

CLASS I, SECTION IV—2

- 23 William Hovgaard.....Brooklyn, N. Y.
 30 George Edmond Russell.....Lexington

CLASS II—NATURAL AND PHYSIOLOGICAL SCIENCES—7

CLASS II, SECTION I—4

- 09 Reginald Aldworth Daly.....Cambridge
 [03] 44 Charles Palache.....Cambridge
 17 Percy Edward Raymond.....Lexington
 11 Hervey Woodburn Shimer.....Hingham

CLASS II, SECTION II—1

- 29 Joseph Horace Faull.....Cambridge

CLASS II, SECTION III—1

- 15 Charles Thomas Brues.....Newtonville

CLASS II, SECTION IV—1

- 15 Reid Hunt.....Boston

CLASS III—THE SOCIAL ARTS—5

CLASS III, SECTION I—1

- (28) 32 Edmund Allen Whitman.....Cambridge

CLASS III, SECTION II—1

- 31 Sidney Bradshaw Fay.....Cambridge

CLASS III, SECTION III,—2

- 32 William James Cunningham.....Cambridge
 36 Elton Mayo.....Polesden Lacey, England

CLASS III, SECTION IV—1

- 36 Clair Elsmere Turner.....Arlington

CLASS IV—THE HUMANITIES—16

CLASS IV, SECTION I—2

- 28 Walter Fenno Dearborn.....Cambridge
 21 William Ernest Hocking.....Madison, N. H.

CLASS IV, SECTION II—5

- 12 George Henry Chase.....Cambridge
 21 William Scott Ferguson.....Cambridge
 33 Henry Thatcher Fowler.....Harmony, R. I.
 22 George La Piana.....Wellesley
 20 Charles Howard McIlwain.....Princeton, N. J.

CLASS IV, SECTION III—5

- 30 James Geddes, Jr.....Brookline
 38 Richmond Laurin Hawkins.....Cambridge
 32 Ernest Felix Langley.....Cambridge
 44 La Rue Van Hook.....New York, N. Y.
 33 George Benson Weston.....Cambridge

CLASS IV, SECTION IV—4

- 29 Charles Townsend Copeland.....Cambridge
 41 Archibald Thompson Davison.....Lincoln
 29 Edward Burlingame Hill.....Francestown, N. H.
 [35] 44 Walter Raymond Spalding.....Cambridge

FOREIGN HONORARY MEMBERS—119

(Number limited to one hundred and fifty)

CLASS I—MATHEMATICAL AND PHYSICAL
SCIENCES—31SECTION I—*Mathematics and Astronomy*—12

- 39 Arnaud Denjoy Paris
 34 Ronald Aylmer Fisher Cambridge, England
 20 Jacques Salomon Hadamard Paris
 27 Ejnar Hertzsprung Leiden
 45 Sir Harold Spencer Jones Greenwich
 46 Bertil Lindblad Stockholm
 47 Edward Arthur Milne Oxford
 46 Jan Hendrik Oort Leiden
 47 Meghnad N. Saha Calcutta
 47 G. A. Shajn Simeis, U. S. S. R.
 15 Charles Jean de la Vallée Poussin Louvain
 29 Hermann Weyl Princeton, N. J.

CLASS I, SECTION II—*Physics*—6

- 29 Vilhelm Frimann Koren Bjerknes Oslo
 45 Niels Bohr Copenhagen
 24 Albert Einstein Princeton, N. J.
 29 James Franck Chicago, Ill.
 29 Abram F. Joffé Leningrad
 47 Sir George Paget Thomson London

CLASS I, SECTION III—*Chemistry*—7

- 29 Johannes N. Brönsted Copenhagen
 27 Peter Debye Ithaca, N. Y.
 33 Jaroslav Heyrovsky Prague
 33 Fritz Paneth Durham
 38 Leopold Ruzicka Zürich
 38 Nevil Vincent Sidgwick Oxford
 29 Heinrich Wieland Munich

CLASS I, SECTION IV—*Technology and Engineering*—6

- 36 Edward Victor Appleton London
 46 Clarence Decatur Howe Ottawa
 34 Luigi Lombardi Rome
 29 Ludwig Prandtl Göttingen
 29 Emil Probst Oxford
 31 Karl Willy Wagner Friedrichsdorf

CLASS II—NATURAL AND PHYSIOLOGICAL
SCIENCES—29SECTION I—*Geology, Mineralogy, and Physics
of the Globe*—6

- 36 Raoul Blanchard Grenoble, France

- 29 Léon William Collet Geneva
 34 Arthur Holmes Edinburgh
 22 Emmanuel de Margerie Paris
 44 Ezequiel Ordoñez Mexico, D. F.
 47 Wong Wen-hao Nanking

CLASS II, SECTION II—*Botany*—8

- 32 Frederick Orpen Bower Ripon
 46 Rudolf Florin Stockholm
 47 P. Maheshwari Dacca, India
 32 Kingo Miyabe Sapporo, Japan
 42 Lorenzo Raimundo Parodi Buenos Aires
 47 Alf Erling Persild Ottawa
 29 Otto Renner Jena
 35 Sir William Wright Smith Edinburgh

CLASS II, SECTION III—*Zoology and Physiology*—9

- 38 Edgar Douglas Adrian Cambridge, England
 20 Maurice Caullery Paris
 38 Emmanuel Fauré-Frémiet Paris
 34 Archibald Vivian Hill London
 41 Bernado Alberto Houssay Buenos Aires
 47 Augustus Daniel Imms . Tipton St. John, Devonshire
 31 August Krogh Copenhagen
 30 Louis Édouard Lapicque Paris
 28 Sir D'Arcy Wentworth Thompson St. Andrews

CLASS II, SECTION IV—*Medicine and Surgery*—6

- 39 Sir Aldo Castellani Rome
 27 Sir Henry Hallett Dale London
 33 Sir Arthur Keith London
 28 Mikinosuke Miyajima Tokyo
 18 Sir Charles Scott Sherrington . Cambridge, England
 36 (Jean) Hyacinthe Vincent Paris

CLASS III—THE SOCIAL ARTS—30

SECTION I—*Jurisprudence*—12

- 44 Victor Andres Belaunde Lima
 47 Paal Berg Oslo
 38 Mircea Djuvara Bucharest
 33 François Geny Nancy
 38 Arthur Lehman Goodhart Oxford
 39 Wilfrid Arthur Greene, Baron Greene
 Holmbury St. Mary, Surrey
 33 Hans Kelsen Berkeley, Cal.
 38 Rt. Hon. Lord Macmillan Ewhurst, Surrey
 33 Juljusz Makarewicz Lwów

- 33 Giorgio Del Vecchio.....Rome
 38 Rt. Hon. Lord Wright.....Burbage, Wilts
 38 John C. H. Wu.....Vatican City

SECTION II—*Government, International Law,
and Diplomacy*—5

- 38 Dionisio Anzilotti.....Rome
 46 Winston Churchill.....London
 32 Paul Claudel.....Paris
 32 Hu Shih.....Peiping
 38 Kenzo Takayanagi.....Tokyo

SECTION III—*Economics and Sociology*—9

- 32 Arthur Lyon Bowley.....Haslemere, Surrey
 39 Henry Clay.....Oxford
 44 Daniel Cosío Villegas.....Mexico, D. F.
 35 Luigi Einaudi.....Turin
 32 Ralph George Hawtrey.....London
 35 René Maunier.....Paris
 28 Arthur Cecil Pigou.....Cambridge, England
 32 Charles Rist.....Versailles
 45 Dennis Holme Robertson.....Cambridge, England

SECTION IV—*Administration and Affairs*—4

- 33 Gösta A. Bagge.....Stockholm
 38 Heinrich Brüning.....Cambridge, Mass.
 45 Alfredo Lorenzo Palacios.....Buenos Aires
 38 B. Seeböhm Rowntree.....North Dean, Bucks

CLASS IV—THE HUMANITIES—29

SECTION I—*Theology, Philosophy, and Psychology*—6

- 28 Benedetto Croce.....Naples
 29 Étienne Gilson.....Melun

- 28 Wolfgang Köhler.....Swarthmore, Pa.
 37 Henri Piéron.....Paris
 46 Francisco Romero.....Buenos Aires
 47 Godfrey Hilton Thomson.....Edinburgh

SECTION II—*History, Archaeology, and Anthropology*—5

- 33 Rafael Altamira y Crevea.....Madrid
 36 Marcel Aubert.....Paris
 33 Friedrich Meinecke.....Berlin-Dahlem
 40 Martin Persson Nilsson.....Lund
 31 George Macaulay Trevelyan.....Cambridge, England

SECTION III—*Philology*—9

- 44 Amado Alonso.....Arlington, Mass.
 47 Hamilton Alexander Rosskeen Gibb.....Oxford
 47 Joseph Klausner.....Jerusalem
 36 Paul Kretschmer.....Vienna
 32 Paul Mazon.....Paris
 17 Ramón Menéndez Pidal.....Madrid
 45 Tomás Navarro Tomás.....New York, N. Y.
 [12] 28 Hanns Oertel.....Munich
 32 Frederick William Thomas.....Bodicote nr. Banbury

SECTION IV—*The Fine Arts and Belles Lettres*—9

- 40 Fernand Baldensperger.....Paris
 30 Alfredo Casella.....Rome
 40 Paul Hindemith.....New Haven, Conn.
 34 Serge Koussevitzky.....Boston
 27 Gilbert Murray.....Oxford
 31 Edgar Allison Peers.....Liverpool
 27 Henri Rabaud.....Paris
 41 Jean Julius Christian Sibelius.....Helsinki
 40 Igor Stravinsky.....Hollywood, Cal

ALPHABETICAL INDEX TO LISTS OF MEMBERS

The letters F, FE and FHM refer to the lists of Fellows, Fellows Emeriti and Foreign Honorary Members, respectively. The class and section are indicated by the numerals following.

- | | | |
|----------------------------------|------------------------------|-------------------------------|
| Abbot, C. G. F, I: 1 | Batchelder, C. F. F, III: 4 | Bovie, W. T. F, II: 3 |
| Abrams, L. R. F, II: 2 | Bateman, A. M. F, II: 1 | Bowen, N. L. F, II: 1 |
| Adams, C. A. F, I: 4 | Bates, H. M. F, III: 1 | Bower, F. O. FHM, II: 2 |
| Adams, C. F. F, III: 4 | Bates, W. N. F, IV: 3 | Bowles, E. L. F, I: 4 |
| Adams, C. R. F, I: 1 | Bauer, W. F, II: 4 | Bowley, A. L. FHM, III: 3 |
| Adams, R. F, I: 3 | Baxter, G. P. F, I: 3 | Bowman, I. F, II: 1 |
| Adams, W. S. F, I: 1 | Baxter, J. P., 3d. F, IV: 2 | Boyden, E. A. F, II: 3 |
| Adrian, E. D. FHM, II: 3 | Beadle, G. W. F, II: 3 | Branch, C. R. F, III: 1 |
| Agassiz, G. R. F, I: 1 | Beattie, J. A. F, I: 3 | Bremer, J. L. F, II: 3 |
| Ahern, M. J. F, IV: 1 | Beebe-Center, J. G. F, IV: 1 | Bridgman, P. W. F, I: 2 |
| Aiken, H. H. F, I: 1 | Beers, R. F. F, II: 1 | Briggs, L. J. F, I: 2 |
| Albright, F. F, II: 4 | Beeson, C. H. F, IV: 3 | Brigham, C. S. F, IV: 2 |
| Allen, A. W. F, II: 4 | Belaunde, V. A. FHM, III: 1 | Brightman, E. S. F, IV: 1 |
| Alonso, A. FHM, IV: 3 | Belding, D. L. F, II: 4 | Brinton, C. F, IV: 2 |
| Altamira y Crevea, R. FHM, IV: 2 | Bell, S. F, III: 1 | Brönsted, J. N. FHM, I: 3 |
| Alter, C. M. F, III: 4 | Benedict, F. G. F, II: 3 | Bronner, A. F. F, III: 3 |
| Amdur, I. F, I: 3 | Benedict, R. F. F, IV: 2 | Brooks, C. F. F, II: 1 |
| Ames, A., Jr. F, I: 2 | Bennett, A. A. F, I: 1 | Brown, D. V. F, III: 3 |
| Ames, O. F, II: 2 | Benson, F. W. F, IV: 4 | Brown, T. H. F, III: 3 |
| Anderson, E. F, II: 2 | Berg, P. FHM, III: 1 | Bruce, H. A. F, IV: 1 |
| Angell, J. R. F, IV: 1 | Berle, A. A., Jr. F, III: 4 | Brüning, H. FHM, III: 4 |
| Angell, J. W. F, III: 3 | Berry, C. H. F, I: 4 | Brues, C. T. FE, II: 3 |
| Anzilotti, D. FHM, III: 2 | Bevis, H. L. F, III: 2 | Bryan, K. F, II: 1 |
| Appleton, E. V. FHM, I: 4 | Bigelow, H. A. F, III: 1 | Buck, C. D. F, IV: 3 |
| Archibald, R. C. F, I: 1 | Bigelow, H. B. F, II: 3 | Buerger, M. J. F, II: 1 |
| Atwood, W. W. F, II: 1 | Bigelow, R. P. F, II: 3 | Bundy, H. H. F, III: 2 |
| Aub, J. C. F, II: 4 | Billings, M. P. F, II: 1 | Bunker, J. W. M. F, II: 3 |
| Aubert, M. FHM, IV: 2 | Birch, F. F, I: 2 | Burbank, H. H. F, III: 3 |
| Ault, W. O. F, IV: 2 | Birkhoff, G. F, I: 1 | Burdell, E. S. F, III: 4 |
| Avery, O. T. F, II: 4 | Bixler, J. S. F, IV: 1 | Burgin, R. F, IV: 4 |
| Ayer, J. B. F, II: 4 | Bjerknes, V. F. K. FHM, I: 2 | Burwell, C. S. F, II: 4 |
| Bacon, L. F, IV: 4 | Blake, C. H. F, II: 3 | Bush, J. N. D. F, IV: 4 |
| Bagge, G. A. FHM, III: 4 | Blake, R. P. F, IV: 2 | Bush, V. F, I: 4 |
| Bailey, I. W. F, II: 2 | Blakeslee, A. F. F, II: 2 | Cabot, G. L. F, III: 4 |
| Bailey, L. H. F, II: 2 | Blanchard, A. A. F, I: 3 | Cabot, T. D. F, III: 4 |
| Bainbridge, K. T. F, I: 2 | Blanchard, R. FHM, II: 1 | Cabot, W. B. F, IV: 2 |
| Baker, G. P. F, III: 3 | Blanshard, B. F, IV: 1 | Cadbury, H. J. F, IV: 2 |
| Baker, J. G. F, I: 1 | Bliss, G. A. F, I: 1 | Cady, W. G. F, I: 2 |
| Balch, F. G. F, II: 4 | Blumer, G. F, II: 4 | Caldwell, R. G. F, III: 2 |
| Balch, F. N. F, III: 1 | Bock, A. V. F, II: 4 | Campbell, C. G. F, IV: 2 |
| Baldensperger, F. FHM, IV: 4 | Bogert, M. T. F, I: 3 | Campbell, D. H. F, II: 2 |
| Ball, E. G. F, I: 3 | Bohr, N. FHM, I: 2 | Campbell, G. A. F, I: 2 |
| Bancroft, W. D. F, I: 3 | Bok, B. J. F, I: 1 | Campbell, L. L. F, I: 2 |
| Banks, N. F, II: 3 | Bonbright, J. C. F, III: 3 | Capps, E. F, IV: 3 |
| Bard, P. F, II: 3 | Bonner, C. F, IV: 3 | Carmichael, L. F, IV: 1 |
| Barnard, C. I. F, III: 4 | Bonner, R. J. F, IV: 3 | Carpenter, F. M. F, II: 1 |
| Barnes, J. L. F, I: 1 | Booth, H. S. F, I: 3 | Carpenter, J. A. F, IV: 4 |
| Barnett, S. J. F, I: 2 | Borchard, E. M. F, III: 2 | Carpenter, T. M. F, II: 3 |
| Barrow, W. L. F, I: 4 | Borgese, G. A. F, IV: 3 | Casella, A. FHM, IV: 4 |
| Barrows, H. K. F, I: 4 | Boring, E. G. F, IV: 1 | Casey, R. P. F, IV: 1 |
| Bartlett, P. D. F, I: 3 | Bosworth, W. F, IV: 4 | Castellani, Sir A. FHM, II: 4 |

- Castle, W. B. F, II: 4
 Castle, W. E. F, II: 3
 Castle, W. R., Jr. F, III: 2
 Caullery, M. FHM, II: 3
 Chaffee, E. L. F, I: 2
 Chamberlain, J. P. F, III: 2
 Chamberlain, S. F, IV: 4
 Chamot, E. M. F, I: 3
 Chandrasekhar, S. F, I: 1
 Chase, G. H. FE, IV: 2
 Cheever, D. F, II: 4
 Christian, H. A. F, II: 4
 Churchill, W. FHM, III: 2
 Claffin, W. H., Jr. F, III: 4
 Clark, J. M. F, III: 3
 Clark, W. E. F, IV: 3
 Clark, W. I. F, II: 4
 Claudel, P. FHM, III: 2
 Clay, H. FHM, III: 3
 Cleland, R. E. F, II: 2
 Cleveland, L. R. F, II: 3
 Clifton, C. D. F, IV: 4
 Coffman, G. R. F, IV: 3
 Cohn, E. J. F, II: 3
 Cole, A. H. F, III: 3
 Cole, R. F, II: 4
 Collet, L. W. FHM, II: 1
 Collins, S. C. F, I: 3
 Compton, A. H. F, I: 2
 Compton, K. T. F, I: 2
 Comstock, A. L. F, III: 4
 Comstock, D. F. F, I: 2
 Conant, J. B. F, I: 3
 Conant, K. J. F, IV: 4
 Condon, E. U. F, I: 2
 Conklin, E. G. F, II: 3
 Constable, W. G. F, IV: 4
 Coolidge, J. L. F, I: 1
 Coolidge, W. D. F, I: 2
 Coon, C. S. F, IV: 2
 Cope, A. C. F, I: 3
 Copeland, C. T. FE, IV: 4
 Copeland, M. F, II: 3
 Cosío Villegas, D. FHM, III: 3
 Crane, R. S. F, IV: 3
 Crane, R. T. F, III: 2
 Crawford, F. H. F, I: 2
 Crew, H. F, I: 2
 Croce, B. FHM, IV: 1
 Croll, M. W. F, IV: 3
 Cross, H. F, I: 4
 Cross, P. C. F, I: 3
 Crozier, W. J. F, II: 3
 Cunningham, W. J. FE, III: 3
 Cushman, J. A. F, II: 3
 Dahl, O. G. C. F, I: 4
 Dale, Sir H. H. FHM, II: 4
 Daly, R. A. FE, II: 1
 Damon, S. F. F, IV: 4
 David, D. K. F, III: 4
 Davis, B. M. F, II: 2
 Davis, H. F, II: 3
 Davis, H. N. F, I: 2
 Davis, T. L. F, I: 3
 Davison, A. T. FE, IV: 4
 Davisson, C. J. F, I: 2
 Dawes, C. L. F, I: 4
 Dawson, A. B. F, II: 3
 Day, A. L. F, I: 2
 Day, C. F, III: 3
 Day, E. E. F, III: 4
 Dearborn, W. F. FE, IV: 1
 Debye, P. FHM, I: 3
 Den Hartog, J. P. F, I: 4
 Denjoy, A. FHM, I: 1
 Dennett, T. F, III: 2
 Dennison, H. S. F, III: 4
 Detwiler, S. R. F, II: 3
 Dewey, B. F, I: 4
 Dewing, A. S. F, III: 3
 Dickey, J. S. F, III: 2
 Dickinson, J. F, III: 1
 Dickson, L. E. F, I: 1
 Dill, D. B. F, II: 3
 Dillon, T. H. F, I: 4
 Dinsmoor, W. B. F, IV: 2
 Djuvara, M. FHM, III: 1
 Dodge, B. O. F, II: 2
 Dodge, R. G. F, III: 1
 Doering, C. R. F, III: 3
 Donham, W. B. F, III: 3
 Dos Passos, J. R. F, IV: 4
 Douglas, J. F, I: 1
 Doyle, H. G. F, IV: 3
 Draper, C. S. F, I: 4
 Du Bois, E. F. F, II: 4
 Du Bridge, L. A. F, I: 2
 Ducasse, C. J. F, IV: 1
 Duff, A. W. F, I: 2
 Dun, A. F, IV: 1
 Duncan, J. C. F, I: 1
 Dunn, G. F, I: 4
 Durand, W. F. F, I: 4
 Eames, A. J. F, II: 2
 Edgell, G. H. F, IV: 4
 Edgerton, F. F, IV: 3
 Edsall, J. T. F, I: 3
 Edwards, D. F. F, III: 4
 Einaudi, L. FHM, III: 3
 Einstein, A. FHM, I: 2
 Elisséeff, S. F, IV: 3
 Emerson, R. A. F, II: 2
 Emerson, W. F, IV: 4
 Emmons, H. W. F, I: 4
 Enders, J. F. F, II: 4
 Erskine, J. F, IV: 4
 Esselen, G. J. F, I: 3
 Evans, A. W. F, II: 2
 Evans, G. C. F, I: 1
 Evans, H. M. F, II: 3
 Evans, R. D. F, I: 2
 Evans, W. L. F, I: 3
 Ewell, A. W. F, I: 2
 Fair, G. M. F, I: 4
 Fairchild, F. R. F, III: 3
 Farnsworth, H. E. F, I: 2
 Faulkner, J. M. F, II: 4
 Faull, J. H. FE, II: 2
 Fauré-Frémiet, E. FHM, II: 3
 Fay, S. B. FE, III: 2
 Ferguson, W. S. FE, IV: 2
 Fergusson, S. P. F, II: 1
 Fernald, M. L. F, II: 2
 Fetter, F. A. F, III: 3
 Field, F. T. F, III: 1
 Field, W. L. W. F, III: 4
 Fieser, L. F. F, I: 3
 Finland, M. F, II: 4
 Fisher, R. A. FHM, I: 1
 Fiska, C. H. F, II: 3
 Fitz, R. F, II: 4
 Flanders, R. E. F, III: 4
 Florin, R. FHM, II: 2
 Forbes, A. F, II: 3
 Forbes, E. W. F, IV: 4
 Forbes, G. S. F, I: 3
 Forbes, W. C. F, III: 2
 Ford, H. S. F, III: 4
 Ford, J. D. M. F, IV: 3
 Fosdick, R. B. F, III: 4
 Fowler, H. T. FE, IV: 2
 Frame, J. E. F, IV: 1
 Franck, J. FHM, I: 2
 Frank, P. F, I: 2
 Franklin, P. F, I: 1
 Freeman, R. E. F, III: 3
 Friedrich, C. J. F, III: 2
 Frost, R. F, IV: 4
 Fuess, C. M. F, IV: 2
 Fuller, L. L. F, III: 1
 Fulton, J. F. F, II: 3
 Furniss, E. S. F, III: 2
 Gamble, J. L. F, II: 4
 Gast, P. R. F, II: 2
 Geddes, J., Jr. FE, IV: 3
 Geny, F. FHM, III: 1
 Gesell, A. L. F, II: 3
 Gibb, H. A. R. FHM, IV: 3
 Gibson, R. F, II: 1
 Gilboy, G. F, I: 4
 Gilson, E. FHM, IV: 1
 Glueck, S. F, III: 3
 Goodale, J. L. F, II: 4
 Goodhart, A. L. FHM, III: 1
 Goodrich, H. F. F, III: 1
 Goodrich, W. F, IV: 4
 Goodwin, H. M. F, I: 2
 Graham, C. H. F, IV: 1
 Graton, L. C. F, II: 1
 Gray, L. H. F, IV: 3

- Green, T. F. F, III: 1
 Greene, Baron. FHM, III: 1
 Greene, J. D. F, III: 4
 Greene, W. C. F, IV: 3
 Gregory, H. E. F, II: 1
 Gregory, W. K. F, II: 3
 Grew, J. C. F, III: 2
 Grinnell, F. W. F, III: 1
 Griswold, E. N. F, III: 1
 Gropius, W. F, IV: 4
 Gulick, C. B. F, IV: 3
 Guthrie, E. R. F, IV: 1
 Hadamard, J. S. FHM, I: 1
 Haertlein, A. F, I: 4
 Haig, R. M. F, III: 3
 Haines, C. G. F, III: 2
 Hall, J. L. F, III: 1
 Ham, T. H. F, II: 4
 Hamilton, E. J. F, III: 3
 Hand, A. N. F, III: 1
 Hand, L. F, III: 1
 Hardy, A. C. F, I: 2
 Harmon, A. M. F, IV: 3
 Harno, A. J. F, III: 1
 Harris, L. F, I: 3
 Harris, S. E. F, III: 3
 Harrison, G. R. F, I: 2
 Harrison, R. G. F, II: 4
 Hastings, A. B. F, I: 3
 Hatch, W. H. P. F, IV: 1
 Havens, R. D. F, IV: 3
 Hawkins, R. L. FE, IV: 3
 Hawtrey, R. G. FHM, III: 3
 Hazen, H. L. F, I: 4
 Healy, W. F, IV: 1
 Hencken, H. O. F, IV: 2
 Hendrickson, G. L. F, IV: 3
 Hertzprung, E. FHM, I: 1
 Heyrovsky, J. FHM, I: 3
 Hill, A. V. FHM, II: 3
 Hill, B. H. F, IV: 2
 Hill, E. B. FE, IV: 4
 Hille, E. F, I: 1
 Hillyer, R. S. F, IV: 4
 Hindemith, P. FHM, IV: 4
 Hippel, A. R. von. F, I: 4
 Hisaw, F. L. F, II: 3
 Hitchcock, F. L. FE, I: 1
 Hoadley, L. F, II: 3
 Hoagland, D. R. F, II: 2
 Hoagland, H. F, II: 3
 Hockett, R. C. F, I: 3
 Hocking, W. E. FE, IV: 1
 Holborn, H. F, III: 2
 Holcombe, A. N. F, III: 2
 Holmes, A. FHM, II: 1
 Holmes, E. J. F, III: 4
 Holmes, H. W. F, III: 3
 Holmes, S. J. F, II: 3
 Hooker, S. B. F, II: 4
 Hooton, E. A. F, IV: 2
 Hopkins E. M. F, III: 4
 Hopkinson, C. F, IV: 4
 Horwood, M. P. F, I: 4
 Hoskins, H. L. F, IV: 2
 Hoskins, R. G. F, II: 3
 Houssay, B. A. FHM, II: 3
 Hovgaard, W. FE, I: 4
 Howard, L. O. F, II: 3
 Howard, W. G. F, IV: 3
 Howe, C. D. FHM, I: 4
 Howe, M. A. DeW. F, IV: 4
 Howe, M. DeW. F, III: 1
 Howe, P. R. F, II: 4
 Hu Shih. FHM, III: 2
 Hubbard, J. C. F, I: 2
 Hudnut, J. F, IV: 4
 Hughes, C. E. F, III: 1
 Hull, C. L. F, IV: 1
 Hull, G. F. F, I: 2
 Hume, E. E. F, II: 4
 Humphreys, W. J. F, II: 1
 Hunsaker, J. C. F, I: 4
 Hunt, F. V. F, I: 2
 Hunt, R. FE, II: 4
 Huntington, A. M. F, IV: 4
 Huntington, E. V. F, I: 1
 Huntress, E. H. F, I: 3
 Hurlbut, C. S., Jr. F, II: 1
 Imms, A. D. FHM, II: 3
 Iselin, C. O. F, II: 1
 Jack, J. G. F, II: 2
 Jack, J. R. F, I: 4
 Jackson, D. C. F, I: 4
 Jackson, H., Jr. F, II: 4
 Jackson, R. T. F, II: 1
 Jackson, W. A. F, IV: 4
 Jaeger, W. W. F, IV: 3
 Jaggat, T. A. F, II: 1
 Janeway, C. A. F, II: 4
 Jellinek, E. M. F, I: 1
 Jessup, P. C. F, III: 2
 Jewett, F. B. F, I: 4
 Joffé, A. F. FHM, I: 2
 Johnson, L. J. F, I: 4
 Johnson, M. M. F, III: 1
 Johnston, I. M. F, II: 2
 Jones, D. F. F, II: 2
 Jones, H. M. F, IV: 4
 Jones, Sir H. S. FHM, I: 1
 Jordan, W. K. F, IV: 2
 Joslin, E. P. F, II: 4
 Keefer, C. S. F, II: 4
 Keenan, J. H. F, I: 4
 Keith, Sir A. FHM, II: 4
 Kelsen, H. FHM, III: 1
 Kemble, E. C. F, I: 2
 Kendall, H. P. F, III: 4
 Keniston, H. F, IV: 3
 Kent, R. G. F, IV: 3
 Keyes, F. G. F, I: 3
 Killian, J. R., Jr. F, III: 4
 Kinkeldey, O. F, IV: 4
 King, R. W. P. F, I: 2
 Kistiakowsky, G. B. F, I: 3
 Klausner, J. FHM, IV: 3
 Kluckhohn, C. K. M. F, IV: 2
 Knight, F. H. F, III: 3
 Knudson, A. C. F, IV: 1
 Köhler, W. FHM, IV: 1
 Koussevitzky, S. FHM, IV: 4
 Kraus, C. A. F, I: 3
 Kretschmer, P. FHM, IV: 3
 Kroeber, A. L. F, IV: 2
 Krogh, A. FHM, II: 3
 Kurath, H. F, IV: 3
 Lamb, A. B. F, I: 3
 Lamont, T. W. F, III: 4
 Lampland, C. O. F, I: 1
 Lancaster, H. C. F, IV: 3
 Land, E. H. F, I: 2
 Landis, E. M. F, II: 3
 Landis, J. M. F, III: 1
 Lane, A. C. F, II: 1
 Langley, E. F. FE, IV: 3
 Langmuir, I. F, I: 3
 Lansing, A. F, IV: 2
 La Piana, G. FE, IV: 2
 Lapique, L. E. FHM, II: 3
 Larsen, E. S., Jr. F, II: 1
 Lashley, K. S. F, IV: 1
 Lawrence, E. O. F, I: 2
 Lawrence, R. R. F, I: 4
 Lawrence, W. H. F, I: 4
 Lawson, A. C. F, II: 1
 Lee, R. I. F, II: 4
 Leeds, M. E. F, III: 4
 Leith, C. K. F, II: 1
 Leland, W. G. F, IV: 2
 Lessells, J. M. F, I: 4
 Levine, S. A. F, II: 4
 Levinson, N. F, I: 1
 Lewis, C. I. F, IV: 1
 Lewis, F. T. F, II: 3
 Lewis, W. K. F, I: 3
 Lillie, R. S. F, II: 3
 Lindblad, B. FHM, I: 1
 Lindsay, R. B. F, I: 2
 Linforth, I. M. F, IV: 3
 Lingelbach, W. E. F, IV: 2
 Little, C. C. F, III: 4
 Livingston, B. E. F, II: 2
 Locke, E. A. F, II: 4
 Lombardi, L. FHM, I: 4
 Longcope, W. T. F, II: 4
 Loofbourow, J. R. F, II: 3
 Lord, M. E. F, IV: 4
 Lowe, E. A. F, IV: 3
 Lowell, R. F, III: 4
 Lull, R. S. F, II: 3

- Lund, F. B. F, II: 4
 Lutz, B. R. F, II: 3
 Luyten, W. J. F, I: 1
 Lyman, T. F, I: 2
 McCrea, R. C. F, III: 3
 McEwen, G. F. F, II: 1
 MacGregor, C. W. F, I: 4
 McIlwain, C. H. FE, IV: 2
 MacInnes, D. A. F, I: 3
 MacIver, R. M. F, III: 3
 McKeehan, L. W. F, I: 2
 McKeon, R. P. F, IV: 1
 MacLane, S. F, I: 1
 McLaren, W. W. F, III: 3
 McLaughlin, D. H. F, II: 1
 MacLaurin, W. R. F, III: 3
 Macmillan, Lord. FHM, III: 1
 McNair, M. P. F, III: 3
 Macneil, S. F, III: 1
 MacNider, W. de B. F, II: 4
 Maginnis, C. D. F, IV: 4
 Magruder, C. F, III: 1
 Maheshwari, P. FHM, II: 2
 Makarewicz, J. FHM, III: 1
 Malamud, W. F, II: 4
 Malone, D. F, III: 4
 Mangelsdorf, P. C. F, II: 2
 Manship, P. F, IV: 4
 Margerie, E. de. FHM, II: 1
 Mark, K. L. F, I: 3
 Marks, L. S. F, I: 4
 Marsh, D. L. F, III: 4
 Marshall, L. C. F, III: 3
 Mason, D. G. F, IV: 4
 Mather, F. J. F, IV: 4
 Mather, K. F. F, II: 1
 Maunier, R. FHM, III: 3
 Maxon, W. R. F, II: 2
 Mayo, E. FE, III: 3
 Mazon, P. FHM, IV: 3
 Mead, W. J. F, II: 1
 Mees, C. E. K. F, I: 3
 Meinecke, F. FHM, IV: 2
 Melander, A. L. F, II: 3
 Menéndez, P., R. FHM, IV: 3
 Menzel, D. H. F, I: 1
 Meriam, R. S. F, III: 3
 Meritt, B. D. F, IV: 3
 Merriam, C. E. F, III: 2
 Merrill, E. D. F, II: 2
 Merritt, E. G. F, I: 2
 Metcalf, K. DeW. F, III: 4
 Meyer, K. F. F, II: 3
 Milas, N. A. F, I: 3
 Miller, G. A. F, I: 1
 Miller, G. S. F, II: 3
 Miller, W. J. F, II: 1
 Millikan, R. A. F, I: 2
 Millis, H. A. F, III: 3
 Mills, F. C. F, III: 3
 Milne, E. A. FHM, I: 1
 Mimno, H. R. F, I: 2
 Miner, L. M. S. F, II: 4
 Minot, G. R. F, II: 4
 Mises, R. von. F, I: 4
 Mitchell, S. F, IV: 2
 Mitchell, S. A. F, I: 1
 Mitchell, W. C. F, III: 3
 Mitchell, W. DeW. F, III: 1
 Miyabe, K. FHM, II: 2
 Miyajima, M. FHM, II: 4
 Moe, H. A. F, III: 4
 Monroe, A. E. F, III: 3
 Moreland, E. L. F, I: 4
 Morey, C. R. F, IV: 4
 Morgan, E. M. F, III: 1
 Morison, S. E. F, IV: 2
 Morris, F. K. F, II: 1
 Morse, M. F, I: 1
 Morse, P. M. F, I: 2
 Morton, A. A. F, I: 3
 Moss, W. L. F, II: 4
 Moulton, F. R. F, I: 1
 Mueller, E. F, I: 3
 Mueller, J. H. F, II: 4
 Muller, H. J. F, II: 3
 Mumford, L. F, IV: 4
 Munro, W. B. F, III: 2
 Murdock, K. B. F, IV: 4
 Murray, G. FHM, IV: 4
 Murray, H. A., Jr. F, IV: 1
 Nash, N. B. F, IV: 1
 Navarro, T. FHM, IV: 3
 Neugebauer, O. E. F, IV: 2
 Neumann, J. von. F, I: 1
 Newhouse, W. H. F, II: 1
 Nilsson, M. P. FHM, IV: 2
 Nitze, W. A. F, IV: 3
 Nock, A. D. F, IV: 1
 Nourse, E. G. F, III: 3
 Noyes, G. R. F, IV: 3
 Noyes, W. A., Jr. F, I: 3
 O'Brian, J. L. F, III: 1
 O'Connor, J. F, IV: 1
 Oertel, H. FHM, IV: 3
 Ogburn, W. F. F, III: 3
 Oldenberg, O. F, I: 2
 Olmsted, F. L. F, I: 4
 Oncley, J. L. F, I: 3
 Oort, J. H. FHM, I: 1
 Oppenheimer, J. R. F, I: 2
 Ordoñez, E. FHM, II: 1
 Osgood, R. B. F, II: 4
 Osterhout, W. J. V. F, II: 2
 Page, L. F, I: 2
 Palache, C. FE, II: 1
 Palacios, A. L. FHM, III: 4
 Palmer, W. W. F, II: 4
 Paneth, F. FHM, I: 3
 Park, C. E. F, IV: 1
 Parker, G. H. F, II: 3
 Parkman, H., Jr. F, III: 1
 Parodi, L. R. FHM, II: 2
 Parsons, T. F, III: 3
 Patch, H. R. F, IV: 3
 Paton, W. A. F, III: 3
 Patterson, R. P. F, III: 1
 Pauling, L. C. F, I: 3
 Payne-Gaposchkin, C. F, I: 1
 Pearse, L. F, I: 4
 Pease, A. S. F, IV: 3
 Peers, E. A. FHM, IV: 4
 Peirce, G. J. F, II: 2
 Pender, H. F, I: 4
 Pepper, G. W. F, III: 1
 Peters, J. L. F, II: 3
 Pfeiffer, R. H. F, IV: 2
 Phillips, H. B. F, I: 1
 Phillips, W. F, III: 2
 Philpott, A. J. F, IV: 4
 Pickard, G. W. F, I: 4
 Pierce, G. W. F, I: 2
 Piéron, H. FHM, IV: 1
 Pigou, A. C. FHM, III: 3
 Pilsbry, H. A. F, II: 3
 Pincus, G. F, II: 3
 Piston, W. H. F, IV: 4
 Poor, C. L. F, I: 1
 Porsild, A. E. FHM, II: 2
 Post, C. R. F, IV: 4
 Pound, R. F, III: 1
 Prandtl, L. FHM, I: 4
 Pratt, C. C. F, IV: 1
 Pratt, F. H. F, II: 3
 Pratt, J. H. F, II: 4
 Prescott, S. C. FE, I: 3
 Probst, E. FHM, I: 4
 Purves, C. B. F, I: 3
 Putnam, H. F, III: 4
 Putnam, T. J. F, II: 4
 Qua, S. E. F, III: 1
 Quinby, W. C. F, II: 4
 Rabaud, H. FHM, IV: 4
 Rabi, I. I. F, I: 2
 Rackemann, F. M. F, II: 4
 Rand, H. W. F, II: 3
 Rapport, D. F, II: 3
 Raup, H. M. F, II: 2
 Raymond, P. E. FE, II: 1
 Redfield, A. C. F, II: 3
 Rehder, A. F, II: 2
 Renner, O. FHM, II: 2
 Richards, A. N. F, II: 3
 Richardson, R. G. D. F, I: 1
 Riddle, O. F, II: 3
 Rist, C. FHM, III: 3
 Robertson, D. H. FHM, III: 3
 Robinson, D. M. F, IV: 2
 Robinson, F. N. F, IV: 3
 Roeder, K. D. F, II: 3

- Roethlisberger, F. J. F, III: 3
 Rogers, A. F. F, II: 1
 Rollins, H. E. F, IV: 3
 Romer, A. S. F, II: 3
 Romero, F. FHM, IV: 1
 Root, R. K. F, IV: 3
 Rosanoff, M. A. F, I: 3
 Rossby, C. G. A. F, II: 1
 Rostovtzeff, M. I. F, IV: 2
 Rowntree, B. S. FHM, III: 4
 Rüdénberg, R. F, I: 4
 Ruggles, A. H. F, II: 4
 Ruggles, C. O. F, III: 3
 Ruml, B. F, III: 4
 Russell, F. F. F, II: 4
 Russell, G. E. FE, I: 4
 Russell, H. N. F, I: 1
 Ruthven, A. G. F, II: 3
 Ruzicka, L. FHM, I: 3
 Sachs, P. J. F, IV: 4
 Saha, M. N. FHM, I: 1
 Salter, W. T. F, II: 4
 Salvemini, G. F, III: 2
 Samuelson, P. A. F, III: 3
 Sanders, H. A. F, IV: 3
 Sanders, T. H. F, III: 3
 Sarton, G. F, IV: 2
 Sayre, F. B. F, III: 1
 Scatchard, G. F, I: 3
 Schaller, W. T. F, II: 1
 Schell, E. H. F, III: 4
 Schevill, R. F, IV: 3
 Schmitt, B. E. F, IV: 2
 Schmitt, F. O. F, II: 3
 Schumb, W. C. F, I: 3
 Schumpeter, J. A. F, III: 3
 Scott, A. W. F, III: 1
 Scott, D. F, IV: 2
 Sedgwick, E. F, IV: 4
 Sedgwick, H. D. F, IV: 4
 Selekman, B. M. F, III: 3
 Seymour, C. F, III: 4
 Sez nec, J. J. F, IV: 3
 Shajn, G. A. FHM, I: 1
 Shapley, H. F, I: 1
 Shattuck, G. C. F, II: 4
 Shattuck, H. L. F, III: 4
 Shaw, H. S. F, III: 4
 Sherburn, G. W. F, IV: 3
 Sherrill, H. K. F, IV: 1
 Sherrill, M. S. F, I: 3
 Sherrington, Sir C. S. FHM, II: 4
 Shimer, H. W. FE, II: 1
 Sibelius, J. J. C. FHM, IV: 4
 Sidgwick, N. V. FHM, I: 3
 Simmons, J. S. F, II: 4
 Simpson, S. P. F, III: 1
 Sinnott, E. W. F, II: 2
 Slater, J. C. F, I: 2
 Slipher, V. M. F, I: 1
 Smith, A. C. F, II: 2
 Smith, D. S. F, IV: 4
 Smith, G. M. F, II: 2
 Smith, H. M. F, I: 3
 Smith, L. B. F, I: 3
 Smith, P. F, III: 4
 Smith, R. M. F, II: 4
 Smith, Sir W. W. FHM, II: 2
 Snyder, V. F, I: 1
 Soderberg, R. C. F, I: 4
 Sollmann, T. H. F, II: 4
 Sorokin, P. A. F, III: 3
 Sosman, M. C. F, II: 4
 Spalding, W. R. FE, IV: 4
 Spaulding, F. T. F, III: 3
 Spaulding, H. N. F, III: 4
 Sperry, W. L. F, IV: 1
 Spinden, H. J. F, IV: 2
 Spoehr, H. A. F, II: 2
 Spofford, C. M. F, I: 4
 Sprague, O. M. W. F, III: 3
 Stafford, R. H. F, IV: 1
 Stakman, E. C. F, II: 2
 Starck, T. F, IV: 3
 Stearns, A. W. F, III: 4
 Stebbins, J. F, I: 1
 Stephenson, C. C. F, I: 3
 Stetson, H. C. F, II: 1
 Stetson, H. T. F, I: 1
 Stevens, S. S. F, IV: 1
 Stewart, G. W. F, I: 2
 Stewart, R. B. F, III: 2
 Stock, C. F, II: 1
 Stockbarger, D. C. F, I: 2
 Stockmayer, W. H. F, I: 3
 Stoke, H. W. F, III: 3
 Stratton, J. A. F, I: 2
 Stravinsky, I. FHM, IV: 4
 Street, J. C. F, I: 2
 Strong, R. P. F, II: 4
 Struik, D. J. F, I: 1
 Struve, O. F, I: 1
 Sverdrup, H. U. F, II: 1
 Swan, T. W. F, III: 1
 Takayanagi, K. FHM, III: 2
 Talbot, F. B. F, II: 4
 Tatlock, J. S. P. F, IV: 3
 Taylor, C. H. F, IV: 2
 Taylor, C. L., Jr. F, IV: 1
 Taylor, F. H. F, IV: 4
 Taylor, H. S. F, I: 3
 Teggart, F. J. F, III: 3
 Terman, F. E. F, I: 4
 Terman, L. M. F, IV: 1
 Terzaghi, K. F, I: 4
 Thannhauser, S. J. F, II: 4
 Thimann, K. V. F, II: 2
 Thomas, F. W. FHM, IV: 3
 Thomas, T. H. F, III: 2
 Thompson, Sir D'A. W. FHM, II: 3
 Thompson, M. deK. F, I: 2
 Thompson, R. F, IV: 4
 Thomson, G. H. FHM, IV: 1
 Thomson, Sir G. P. FHM, I: 2
 Thomson, W. F, IV: 3
 Thorn, G. W. F, II: 4
 Thorndike, E. L. F, IV: 1
 Thurston, E. S. F, III: 1
 Thurstone, L. L. F, IV: 1
 Tolman, R. C. F, I: 3
 Torrey, C. C. F, IV: 3
 Tosdal, H. R. F, III: 3
 Tozzer, A. M. F, IV: 2
 Trevelyan, G. M. FHM, IV: 2
 Tucker, D. S. F, III: 3
 Turner, C. E. FE, III: 4
 Twaddell, W. F. F, IV: 3
 Tyzzer, E. E. F, II: 4
 Ulich, R. F, III: 3
 Urey, H. C. F, I: 3
 Usher, A. P. F, III: 3
 Vallarta, M. S. F, I: 2
 Vallée Poussin, C. J. de la. FHM, I: 1
 Van de Graaff, R. J. F, I: 2
 Van Hook, L. R. FE, IV: 3
 Van Vleck, J. H. F, I: 2
 Vaughan, T. W. F, II: 1
 Veblen, O. F, I: 1
 Vecchio, G. Del. FHM, III: 1
 Verhoeff, F. H. F, II: 4
 Viëtor, K. F, IV: 4
 Viets, H. R. F, IV: 2
 Vincent, J. H. FHM, II: 4
 Viner, J. F, III: 3
 Wagner, K. W. FHM, I: 4
 Wagner, M. F, IV: 4
 Walsh, J. L. F, I: 1
 Wambaugh, S. F, III: 2
 Warner, E. P. F, I: 4
 Warren, B. E. F, I: 2
 Warren, C. H. F, II: 1
 Warren, S. F, II: 4
 Washburn, H. B. F, IV: 1
 Watson, J. B. F, IV: 1
 Wearn, J. T. F, II: 4
 Weatherby, C. A. F, II: 2
 Webster, D. L. F, I: 2
 Webster, E. S. F, III: 4
 Weeks, E. A., Jr. F, IV: 4
 Weiser, H. B. F, I: 3
 Welles, S. F, III: 2
 Wells, F. L. F, IV: 1
 Welsh, J. H., Jr. F, II: 3
 Westergaard, H. M. F, I: 4
 Weston, G. B. FE, IV: 3
 Weston, K. E. F, IV: 4
 Weston, W. H., Jr. F, II: 2
 Wetmore, R. H. F, II: 2
 Weyl, H. FHM, I: 1
 Weyssse, A. W. F, II: 3

Whipple, F. L. F, I: 1
White, P. D. F, II: 4
Whitehead, T. N. F, III: 3
Whitlock, H. P. F, II: 1
Whitman, E. A. FE, III: 1
Whitney, W. R. F, I: 3
Whittlesey, D. S. F, II: 1
Widder, D. V. F, I: 1
Wieland, H. FHM, I: 3
Wilbur, J. B. F, I: 4
Wild, P. S., Jr. F, III: 2
Wilkins, E. H. F, IV: 3
Williams, J. H. F, III: 3
Williams, R. S. F, I: 3
Willis, B. F, II: 1
Willits, J. H. F, III: 3
Willoughby, W. F. F, III: 2

Wilson, C. E. F, III: 4
Wilson E. B. F, I: 2
Wilson, E. B., Jr. F, I: 3
Wilson, G. G. F, III: 2
Winlock, H. E. F, IV: 4
Winship, L. L. F, III: 4
Wislocki, G. B. F, II: 3
Wolbach, S. B. F, II: 4
Wolfson, H. A. F, IV: 3
Wolman, L. F, III: 3
Wong, Wen-hao. FHM, II: 1
Wood, R. W. F, I: 2
Woods, F. S. FE, I: 1
Woodworth, R. S. F, IV: 1
Worrell, W. H. F, IV: 3
Wright, Lord. FHM, III: 1

Wright, C. H. C. F, IV: 4
Wright, F. E. F, II: 1
Wright, Q. F, III: 2
Wu, J. C. H. FHM, III: 1
Wulff, J. F, I: 4
Wurster, W. W. F, IV: 4
Wyman, J., Jr. F, II: 3
Wyman, L. C. F, II: 3
Wyzanski, C. E., Jr. F, III: 1
Yeomans, H. A. F, III: 2
Yerkes, R. M. F, II: 3
Young, B. L. F, III: 4
Young, O. D. F, III: 4
Young, R. C. F, I: 3
Zeleny, J. F, I: 2
Zimmerman, C. C. F, III: 3
Zworykin, V. K. F, I: 4

STATUTES

THE AMERICAN ACADEMY OF ARTS AND SCIENCES

Adopted November 8, 1911; amended May 8, 1912, January 8, and May 14, 1913, April 14, 1915, April 12, 1916, April 10, 1918, May 14, 1919, February 8, April 12, and December 13, 1922, February 14, March 14, and October 10, 1923, March 10, 1926, May 9, 1928, April 8, and November 11, 1931, April 12, 1933, February 14, 1934, December 14, 1938, January 11, April 12, 1939, May 8, 1940, May 14, 1941, November 18, 1942, and January 12, 1944, May 9, 1945, November 14, 1945, February 2, 1946, October 9, 1946, and October 8, 1947.

Chapter I

THE ACADEMY AND ITS CORPORATE SEAL

ARTICLE 1. The American Academy of Arts and Sciences is a body politic and corporate by the same name, forever, established by the Council and House of Representatives in General Court of the Province of Massachusetts Bay as recorded in Chap. 46 of the Acts of 1779.

ARTICLE 2. As enacted above, the stated end and design of the institution of the said academy is to promote and encourage the knowledge of the antiquities of America, and of the natural history of the country, and to determine the uses to which the various natural productions of the country may be applied; to promote and encourage medical discoveries, mathematical disquisitions, philosophical enquiries and experiments, astronomical, meteorological and geographical observations; and improvements in agriculture, arts, manufacture and commerce; and, in fine, to cultivate every art and science which may tend to advance the interest, honor, dignity and happiness of a free, independent and virtuous people.

ARTICLE 3. The Corporate Seal of the Academy shall be as here depicted.



ARTICLE 4. The Secretary shall have the custody of the Corporate Seal.

See Chap. v, art. 3; chap. vi, art. 1.

CHAPTER II

MEMBERSHIP AND DUES

ARTICLE 1. The Academy shall consist of Fellows, elected from the citizens or residents of the United States of America, Fellows Emeriti, and Foreign Honorary Members. They are arranged in four Classes, according to the Arts and Sciences in which they are severally proficient, and each Class shall be divided into four Sections, namely:

CLASS I. *The Mathematical and Physical Sciences*

- Section 1. Mathematics and Astronomy
- Section 2. Physics
- Section 3. Chemistry
- Section 4. Technology and Engineering

CLASS II. *The Natural and Physiological Sciences*

- Section 1. Geology, Mineralogy, and Physics of the Globe
- Section 2. Botany

Section 3. Zoology and Physiology

Section 4. Medicine and Surgery

CLASS III. *The Social Arts*

Section 1. Jurisprudence

Section 2. Government, International Law, and Diplomacy

Section 3. Economics and Sociology

Section 4. Administration and Affairs

CLASS IV. *The Humanities*

Section 1. Theology, Philosophy, and Psychology

Section 2. History, Archaeology, and Anthropology

Section 3. Philology

Section 4. The Fine Arts and Belles Lettres

ARTICLE 2. The number of Fellows shall not exceed One thousand, of whom not more than Eight hundred shall be residents of Massachusetts, nor shall there be more than Two hundred and seventy-five in any one Class.

Any Fellow of the Academy on retiring from his academic or other regular duties may, if he so requests in writing, and with the approval of the Council, be transferred to the status of Fellow Emeritus.

Fellows Emeriti shall be exempt from payment of dues. They may not hold elective office in the Academy, nor serve on Standing Committees, nor vote at meetings, but shall have all the other privileges of Fellowship.

Fellows Emeriti shall be separately classified and shall be outside the statutory limit set on the total number of Fellows and the number in a given Class.

See Chap. ix, art. 3; chap. x, art. 1.

ARTICLE 3. The number of Foreign Honorary Members shall not exceed One hundred and fifty. They shall be chosen from citizens of foreign countries most eminent for their discoveries and attainments in any of the Classes above enumerated. There shall be not more than Forty-five in any one Class.

ARTICLE 4. Diplomas signed by the President and the Vice-President of the Class to

which the member belongs, and countersigned by the Secretary, shall be given to Fellows and Foreign Honorary Members.

ARTICLE 5. If any person, after being notified of his election as Fellow or Foreign Honorary Member, shall neglect for six months to accept in writing, his election shall be void.

ARTICLE 6. Every Fellow resident within fifty miles of Boston hereafter elected shall pay an Admission Fee of Ten Dollars: if he shall neglect to pay this Fee within six months of the date of his election, his election shall become void.

Every Fellow resident within fifty miles of Boston shall pay such Annual Dues, not exceeding Fifteen dollars, as shall be voted by the Academy at each Annual Meeting, at which time they shall become due.

Every Fellow residing more than fifty miles from Boston elected after 1938 shall pay, and other non-resident Fellows may pay, Annual Dues equal to one-half the amount set for resident Fellows at each Annual Meeting and due on the same date.

Any Fellow shall be exempt from further payment of Annual Dues who has paid such dues for forty years, or having attained the age of seventy-five, has paid dues for twenty-five years.

Any Fellow may also be exempt from further payment of annual dues upon payment into the treasury of the Academy the sum of Two hundred dollars in addition to his previous payments.

Any Fellow not previously subject to Annual Dues who takes up his residence within fifty miles of Boston, shall pay to the Treasurer, within three months thereafter, Annual Dues for the current year, and if he shall neglect to make this payment within the specified time, after having been notified by the Treasurer of the requirements of this Article of the Statutes, he shall cease to be a Fellow.

ARTICLE 7. Any Fellow, resident or non-resident, who shall neglect to pay his Annual Dues for six months after they are due and who ignores notification by the Treasurer of

the requirements of this Article of the Statutes shall cease to be a Fellow.

ARTICLE 8. Only Fellows who pay Annual Dues or have commuted them may hold elective office in the Academy or serve on Standing Committees or vote at meetings.

ARTICLE 9. Upon petition of any Fellow, the Council may by a majority vote suspend the application of any penalties hereinabove prescribed in this chapter for an additional period of time not longer than three months.

ARTICLE 10. If, in the opinion of a majority of the entire Council, any Fellow or Foreign Honorary Member shall have rendered himself unworthy of a place in the Academy, the Council shall recommend to the Academy the termination of his membership; and if three-fourths of the Fellows present out of a total attendance of not less than fifty at a Stated Meeting, or at a Special Meeting called for the purpose, shall adopt this recommendation, his name shall be stricken from the Roll.

See Chap. iii; chap. vi, art. 5 and 6; chap. x, art. 1.

CHAPTER III

NOMINATION AND ELECTION OF FELLOWS AND FOREIGN HONORARY MEMBERS

The procedure for nomination and election of Fellows and Foreign Honorary Members shall be as follows:

ARTICLE 1. Nominations may be made at any time by any two Fellows in writing on forms to be provided by the Secretary and shall be referred by him to the Committee on Membership.

The Committee on Membership shall meet following the stated meetings of the Academy in May, November, February and March, and at such other times as it may determine, to appraise nominations received by it from the Fellows from time to time, to originate further nominations, and to approve as candidates for election those receiving the favorable vote of two-thirds of the Committee members present in any meeting attended by not less than five of its members.

Immediately following its meeting in February, the Committee shall cause to be sent to

every Fellow a list of nominees, with biographical and professional data thereon, together with names of nominators, for appraisal, expression of preference, or other comment by the Fellows.

The Committee, at its March meeting, shall review all nominations, together with comments by the Fellows thereon, and shall compile a list of approved candidates for the annual election of Fellows and Foreign Honorary Members. It shall present this list together with data pertaining thereto to the Council not later than at the stated meeting of the Council in April.

The Council, by vote of the majority of members present at a meeting, shall make final nominations from the list of approved persons recommended by the Committee on Membership for election by the Fellows.

ARTICLE 2. Election of Fellows and Foreign Honorary Members shall be made by a majority of the Fellows present at the Annual Meeting in May, from the nominations presented at that meeting by the Council.

ARTICLE 3. Each Fellow or Foreign Honorary Member shall be notified in writing by the Secretary immediately following his election.

See Chap. ii; chap. vi, art. 5; chap. x, art. 1; chap. xi, art. 1 (ii).

CHAPTER IV

OFFICERS

ARTICLE 1. The Officers of the Academy shall be a President (who shall be Chairman of the Council), four Vice-Presidents (one from each Class), a Secretary (who shall be Secretary of the Council), a Treasurer, a Librarian, and an Editor, all of whom shall be elected by ballot at the Annual Meeting, and shall take office at the close of that meeting, and shall hold their respective offices for one year, and until others are duly chosen and take office.

There shall be also sixteen Councillors, one from each Section of each Class. At each Annual Meeting four Councillors, one from each Class, shall be elected by ballot to serve for a term of four years, and they shall take office at the close of that meeting, and shall hold office

until others are duly chosen and take office. The same Fellows shall not be eligible for two successive terms.

The Councillors, with the officers previously named, and the Chairmen of the Standing Committees, *ex officio*, shall constitute the Council.

See Chap. xi, art. 1.

ARTICLE 2. If any officer be unable, through death, absence, or disability, to fulfill the duties of his office, or if he shall resign, his place may be filled by the Council in its discretion for any part or the whole of the unexpired term.

ARTICLE 3. At the Stated Meeting in March, the President shall appoint a Nominating Committee of four Fellows having the right to vote, one from each Class. This Committee shall prepare a list of nominees for the several offices to be filled, and for the Standing Committees, and file it with the Secretary not later than four weeks before the Annual Meeting.

ARTICLE 4. Independent nominations for any office, if signed by at least twenty Fellows having the right to vote, and received by the Secretary not less than ten days before the Annual Meeting, shall be included in the election procedure.

ARTICLE 5. The Secretary shall prepare for use in voting at the Annual Meeting a ballot containing the names of all persons duly nominated for office.

CHAPTER V

THE PRESIDENT

ARTICLE 1. The President, or in his absence a Vice-President, shall preside at meetings of the Academy.

See Chap. vi, art. 3.

ARTICLE 2. The President shall be the chief executive officer of the Academy. He shall present to the Council for its consideration all matters pertinent to the interests of the Academy and to the discharge of its obligations to the community or to the advancement of scholarship.

ARTICLE 3. Any deed or writing to which the Corporate Seal is to be affixed, except leases of real estate, shall be executed in the name of the Academy by the President or in the event of his death, absence, or inability, by one of the Vice-Presidents, when thereto duly authorized by the Council.

ARTICLE 4. In case of incapacity of the President, the Council shall designate a Vice-President to carry out the duties of the office.

See Chap. ii, art. 4; chap. iv, art. 1, 3; chap. vi, art. 3; chap. viii, art. 4; chap. x, art. 3; chap. xi, art. 1 (ii), (iii), (x); chap. xii, art. 1.

CHAPTER VI

THE SECRETARY

ARTICLE 1. The Secretary shall provide for the custody of the Charter, Corporate Seal, Statute Book, Journals of the Academy, and other Archives.

ARTICLE 2. He shall be responsible for the correspondence of the Academy and of the Council. At each meeting of the Council he shall present any important communications addressed to the Academy which have been received since the previous meeting, and at the next meeting of the Academy he shall present such matters as the Council may determine.

ARTICLE 3. He shall attend the meetings of the Academy and the Council and shall arrange for the keeping of a faithful record of the attendance and of the proceedings. In the absence of the President and of all the Vice-Presidents, he shall call the meeting to order and preside until a chairman is chosen by majority vote of the Fellows present.

ARTICLE 4. He shall apprise officers and committees of their election or appointment, and inform the Treasurer and the Chairman of each Standing Committee of appropriations of money voted by the Academy.

ARTICLE 5. He shall notify all persons who may be elected Fellows or Foreign Honorary Members, send to each a copy of the Statutes, and on their acceptance issue the proper Diploma. After all elections, he shall insert in the Records the names of the Fellows by whom the successful nominees were proposed.

ARTICLE 6. He shall keep and cause to be printed annually a list of the Fellows and Foreign Honorary Members, arranged in their several Classes and Sections, and a list of Fellows and Foreign Honorary Members of whose deaths he has been informed.

ARTICLE 7. He shall arrange for the preservation of records of the death of Fellows and Foreign Honorary members and biographical notices published on the occasion of their death, or at other times.

See Chap. i, art. 2; chap. ii, art. 4; chap. iii; chap. iv, art. 1, 3, 4, 5; chap. ix, art. 3; chap. xi, art. 1 (iii), 2; chap. xii, art. 1, 3.

CHAPTER VII

THE TREASURER AND THE TREASURY

ARTICLE 1. The Treasurer shall collect all money due or payable to the Academy and all gifts or bequests made to it. He shall pay all bills due and payable by the Academy when approved by the proper officers. He shall sign all leases of real estate in the name of the Academy. He shall be the official custodian of all bonds, stocks and other securities and, with the written approval of any one member of the Committee on Finance, he shall have full authority to sell and transfer, invest and reinvest from time to time in such manner and upon such terms as shall to him seem best, the whole or any part of the personal property of the said Academy.

He shall keep a faithful account of all receipts and expenditures, submit his accounts annually to the Auditing Committee, and render them at the expiration of his term of office, or whenever required to do so by the Academy or the Council.

He shall keep separate accounts of the income of the Rumford Fund, and of all other special Funds, and of the Appropriation thereof, and render them annually.

He shall fund all payments received in commutation of Dues, their income only, to be applied toward current expenditures.

His accounts shall always be open to the inspection of the Council.

ARTICLE 2. He shall report annually to the Council at its March meeting on the expected

income of the various Funds and from all other sources, together with appropriations needed by Officers and Standing Committees for the ensuing fiscal year. He shall also report the names of all Fellows who may be then delinquent in the payment of their Annual Dues.

ARTICLE 3. He shall give such security for the trust reposed in him as the Academy may require.

ARTICLE 4. With the approval of a majority of the Committee on Finance, he may appoint an Assistant Treasurer to perform his duties, for whose acts, as such assistant, he shall be responsible; or, with like approval and responsibility, he may employ any Trust Company doing business in Boston as his agent for the same purpose, the compensation of such Assistant Treasurer or agent to be fixed by the Committee on Finance and paid from the Funds of the Academy.

ARTICLE 5. At the Annual Meeting he shall report in print all his official doings for the preceding year, stating the amount and condition of all the property of the Academy entrusted to him, and the character of the investments.

ARTICLE 6. The Financial Year of the Academy shall begin with the first day of April.

ARTICLE 7. No person or committee shall incur any debt or liability in the name of the Academy, unless in accordance with a previous vote and appropriation therefor by the Academy or the Council, or sell or otherwise dispose of any property of the Academy, except cash or invested funds, without previous consent and approval of the Council.

See Chap. ii, art. 2, 6, 7, 8; chap. iv, art. 1, chap. vi, art. 4; chap. ix, art. 6; chap. xi, art. 1 (i), (iv), (v), art. 2; chap. xii, art. 1.

CHAPTER VIII

THE LIBRARIAN AND THE LIBRARY

ARTICLE 1. The Librarian shall have charge of the Library and keep a correct catalog of it.

ARTICLE 2. The Librarian shall have authority to expend such sums as may be appropriated by the Academy for the purchase, repair, or maintenance of books,

periodicals, etc., and for defraying other necessary expenses connected with the Library.

ARTICLE 3. All books procured from the income of the Rumford Fund or other special funds shall contain a bookplate expressing the fact.

ARTICLE 4. The Librarian shall have the custody of the publications of the Academy. With the advice and consent of the President, he may effect exchanges with other associations.

See Chap. iv, art. 1; chap. xi.

CHAPTER IX

THE EDITOR AND THE PUBLICATIONS

ARTICLE 1. The Editor shall have charge of the conduct through the press of the publications of the Academy. Together with the Committee on Publications he shall determine the contents of the publications.

ARTICLE 2. The publications of the Academy shall be as follows:

(i) The Proceedings shall be published at least semi-annually as soon as may be possible after the Annual May Meeting, and the stated December meeting next following, and shall contain a record of each stated or special meeting of the Academy. They shall be known respectively as the Summer and Winter number of the Proceedings.

The Summer number of the Proceedings shall include reports of the officers and standing committees for the preceding year; a list of the officers, councillors and members of standing committees elected at the preceding Annual Meeting; and such other matter as the Publication Committee may approve.

The Winter number of the Proceedings shall include a current list of officers, councillors, standing committees, Fellows and Foreign Honorary Members; the Statutes of the Academy; the Act of Incorporation of 1780 and its amendments; and such biographical notices or other matter as the Committee on Publications may approve.

In the discretion of the Committee on Publication, interim numbers of the Proceedings may be issued for the publication of accepted serial papers or other scholarly material.

(ii) Memoirs, monographs and volumes of collected papers may be published from time to time.

(iii) The Bulletin of the American Academy of Arts and Sciences shall be published eight times each year preceding the stated meetings, containing notices of such meetings, communications from the council or officers, and such other matter as may be of timely interest to the Fellows.

ARTICLE 3. A copy of the Summer and Winter numbers of the Proceedings shall be mailed to each Fellow, Fellow Emeritus, and Foreign Honorary Member.

A copy of the Bulletin shall be mailed to each Fellow and Fellow Emeritus.

A copy of any Interim number of the Proceedings shall be mailed only to those Fellows, Fellows Emeriti, and Foreign Honorary Members, who shall make written request to the Secretary for that number.

ARTICLE 4. Fellows who pay or have commuted the Annual Dues, Fellows Emeriti, and Foreign Honorary Members shall be entitled, upon written request to the Librarian, to receive gratis one copy of each number of Proceedings, memoirs, monographs or series of collected papers, published by the Academy, which have been issued after their election, and are available.

ARTICLE 5. Not more than Two hundred extra copies of each paper printed in the Proceedings shall be placed at the disposal of the author without charge.

ARTICLE 6. The Editor shall have the authority to expend for printing and other expenses of publication such sums as may be appropriated by the Academy for such purposes; also such sums as may be made available to him by the Council from any source for particular publications under the sponsorship of the Academy.

See Chap. iv, art. 1; chap. xi, art. 1 (vi).

CHAPTER X

THE COUNCIL

ARTICLE 1. The Council shall exercise general supervision over all affairs of the Academy

not explicitly reserved to the Academy as a whole.

It shall consider all nominations of Fellows and Foreign Honorary members duly sent to it by the Committee on Membership, and act upon them in accordance with the provisions of Chapter III.

With the consent of the person concerned it shall have power to present to the Academy a proposal to transfer in respect to status, Class, or Section.

ARTICLE 2. Nine members shall constitute a quorum.

ARTICLE 3. It shall act upon all resignations and forfeitures of membership in the Academy.

It shall appoint all agents and subordinates not otherwise provided for by the Statutes, prescribe their duties, and fix their compensation. They shall hold their respective positions during the pleasure of the Council.

It shall fill any vacancy caused by death, resignation or incapacity of any officer.

ARTICLE 4. It may appoint for terms not exceeding one year, and prescribe the functions of such committees of its number or of the Fellows of the Academy, as it may deem expedient, to facilitate the administration of the affairs of the Academy or to promote its interests.

ARTICLE 5. At the stated March meeting of the Academy it shall recommend for action the appropriations which in the opinion of the Council should be made for the ensuing fiscal year and the Annual Dues therefor.

It may recommend special appropriations at any Stated Meeting of the Academy, or at a Special Meeting, in the call for which such business shall have been included.

See Chap. ii, art. 2, 10; chap. iii, art. 1, 2; chap. iv, art. 1, 2; chap. v, art. 2, 3; chap. vi, art. 2, 3; chap. vii, art. 1, 2, 7; chap. ix, art. 6; chap. xi, art. 1; chap. xii, art. 1, 4, 6.

CHAPTER XI

STANDING COMMITTEES

ARTICLE 1. At the Annual Meeting of the Corporation the following Standing Committees shall be elected by ballot of the Fellows to

serve from the time of their election until their successors shall have been elected.

(1) *The House Committee* shall consist of three Fellows who shall have general charge of maintaining the House of the Academy in suitable condition for the uses thereof approved by the Council.

The Chairman of the House Committee or his designate shall approve in writing all expenditures for repairs, services, supplies or operation of the House, including salaries of House Employees.

The House Committee, in consultation with the Treasurer, shall determine the equitable proportion of expense to be assessed for the use of the facilities of the House, which are approved by the Council for other than Academy activities.

(ii) *The Committee on Membership* shall consist of the President, ex-officio, as Chairman, and eight Fellows, not members of the Council, one from each Class to be elected annually to serve for two years, except that in the initial election one additional Fellow shall be elected from each Class to serve for one year only. It shall have the duties designated to it in Chapter III.

(iii) *The Committee on Meetings* shall consist of the President as Chairman, and the Secretary, ex-officio, and four other Fellows. It shall arrange for meetings of the Academy.

(iv) *The Committee on Finance* shall consist of the Treasurer, ex-officio, as Chairman, and four other Fellows. It shall have general oversight of the investments of the Academy.

(v) *The Auditing Committee* shall consist of two Fellows who shall audit the accounts of the Treasurer with power to employ an expert and to approve his bill.

(vi) *The Committee on Publication* shall consist of the Editor as Chairman, ex-officio, and four other Fellows, one from each Class. It shall have the authority and the responsibility of determining the contents and of effecting the printing of the Publications of the Academy as set forth in Chapter IX.

(vii) *The Permanent Science Fund Committee* shall consist of seven Fellows. It shall

review all applications for grants addressed to it and shall from time to time recommend to the Council appropriate disbursements from the income received by the Academy from the Trustee of the Permanent Science Fund, for carrying out the purposes set forth in the Agreement and Declaration of Trust which governs the use of this Fund.

(viii) *The Rumford Committee* shall consist of seven Fellows. It shall invite applications for pecuniary assistance in support of researches in the fields of heat and light, including X rays, and it alone shall authorize the purchase of books, publications and apparatus at the charge of the income from the Rumford Fund. It shall biennially recommend to the Council a candidate for the reception of the Premium to be awarded in accordance with the Rumford trust, and shall generally see to the proper execution of this trust.

(ix) *The C. M. Warren Committee* shall consist of seven Fellows. It shall invite applications for pecuniary assistance from any person wishing to engage in research in any branch of chemistry and shall recommend to the Council such applications as seem to be worthy of aid, and such other disbursements from income of the C. M. Warren Fund as it deems appropriate to the advancement of research in chemistry.

(x) *The Amory Prize Committee* shall consist of seven Fellows. It shall consider persons eligible and recommend to the Council the award by the President and Fellows of the Amory Prize and a gold medal or other token of honor and merit for each septennium beginning with that which was concluded on November 10, 1933, and thereafter, said award being in recognition of an invention or other contribution in the medical field specified in and according to the terms of the bequest of Francis Amory.

ARTICLE 2. Each Standing Committee shall confine its recommendations and its expenditures to such sum in each fiscal year as shall have been notified to its Chairman by the Secretary of the Academy as appropriations

voted by the Academy, or by the Treasurer as income available for its purposes.

ARTICLE 3. Each Standing Committee shall report to the Academy at the Annual Meeting, its acts of the previous year.

See Chap. iii; chap. iv, art. 1, 3; chap. vi, art. 4; chap. vii, art. 1, 2, 4; chap. ix, art. 1, 2.

CHAPTER XII

MEETINGS, COMMUNICATIONS, AND AMENDMENTS

ARTICLE 1. There shall be annually eight Stated Meetings of the Academy, namely, on the second Wednesday of October, November, December, January, February, March, April, and May. Only at these meetings, or at adjournments thereof regularly notified, or at Special Meetings called for the purpose, shall appropriations of money be made or amendments of the Statutes be effected.

The Stated Meeting in May shall be the Annual Meeting of the Corporation.

Special Meetings shall be called by the Secretary at the request of the President, of the Council, or of ten Fellows having the right to vote; and notifications thereof shall state the purpose for which the meeting is called.

The Council shall have authority, as occasion may demand, to arrange additional meetings and to cancel any of the Statutory meetings, except that meetings for transacting business shall be held as required by the Statutes.

ARTICLE 2. Except as otherwise provided, twenty-five Fellows having the right to vote shall constitute a quorum for the transaction of business at Stated or Special Meetings. Eighteen Fellows shall be sufficient to constitute a meeting for literary or scientific communications and discussions.

ARTICLE 3. Upon the request of the presiding officer or the Secretary, any motion or resolution offered at any meeting shall be submitted in writing.

ARTICLE 4. Fellows may introduce guests at any of the literary or scientific meetings of the Academy.

ARTICLE 5. All amendments to the Statutes, whether proposed by Fellows or by the Council, shall be considered by the Council and reported with recommendations for action to the Academy. At a subsequent Stated Meeting, or at a Special Meeting called for the purpose, the notice for which in either case shall state this proposed amendment, the Academy shall

act upon the amendment. Two-thirds of the Fellows present, in a meeting of not less than forty Fellows, must vote in the affirmative to enact the amendment.

See Chap. ii, art. 6, 10; chap. iii, art. 1, 2; chap. iv, art. 1, 3, 4, 5; chap. v, art. 1; chap. vi, art. 2, 3; chap. vii, art. 2, 5; chap. ix, art. 2; chap. x, art. 5; chap. xi, art. 1, 3.

Proceedings of the American Academy of Arts and Sciences

VOL. 76, No. 1, P. 1-24—FEBRUARY, 1945

THE COMPRESSION OF TWENTY-ONE HALOGEN COMPOUNDS
AND ELEVEN OTHER SIMPLE SUBSTANCES TO 100,000 kg/cm²

By P. W. BRIDGMAN

THE COMPRESSION OF SIXTY-ONE SOLID SUBSTANCES TO
25,000 kg/cm², DETERMINED BY A NEW RAPID METHOD

By P. W. BRIDGMAN

THE COMPRESSION OF TWENTY-ONE HALOGEN COMPOUNDS AND ELEVEN OTHER SIMPLE SUBSTANCES TO 100,000 kg/cm²

By P. W. BRIDGMAN

Presented Oct. 11, 1944.

Received Oct. 17, 1944.

CONTENTS

INTRODUCTION.....	1
METHOD OF MEASUREMENT AND CALCULATION.....	1
EXPERIMENTAL DETAILS.....	2
DISCUSSION OF RESULTS.....	4

INTRODUCTION

In this paper the method previously used¹ in determining the compressions of seventeen elements to 100,000 kg/cm² is extended to a determination of the twenty-one halogen compounds of sodium, potassium, rubidium, caesium, silver, thallium, and ammonium, of the corresponding seven nitrates, of sulfur, of silver bromate, of metallic lead both in the massive and finely powdered condition, and to a redetermination of the compression of metallic indium.

The measurements on sulfur and all the salts except NH_4NO_3 were made in 1941 and early 1942, and have been waiting since for an opportunity for publication. The measurements on NH_4NO_3 , lead, and indium were made early in 1944, when opportunity was found to resume measurements. The apparatus had been left untouched in the interval, and on resumption of work functioned at once, with no important alteration in any of the constants, except for one matter to be mentioned presently.

In addition to the measurements recorded here, data were also obtained for the compressions of arsenic, and of lead sulfide, selenide, and telluride. The frictional resistance to the motion of the piston offered by these hard substances resulted in so great difference between the displacements with increasing and decreasing pressure that it did not seem worth while to subject the measurements to calculation. It can be stated, however, that no new transitions were found in the range above 50,000; the known transitions of the selenide and telluride below 50,000 were again encountered. It will probably be possible to make satisfactory measurements on substances as hard

as these by a modification in technique which has been sufficiently used to show its promise. This consists in enclosing the substance in a thin capsule of indium, by which the stress on the outside of the specimen is reduced to an approximate hydrostatic pressure. Any measurements by this technique will be reserved for a future communication.

METHOD OF MEASUREMENT AND CALCULATION

As compared with the previous work already described in full detail, little change was made in the experimental technique. A revised method of calculation was adopted, however. It will be recalled that the method is a differential one, in which the piston displacement is determined as a function of pressure when the piezometer is filled with the substance under investigation and when filled with gold, it being assumed that the compression of gold is known. In any single run the measured piston displacement is a function not only of the pressure prevailing inside the high pressure piezometer, but also of the hydrostatic pressure in the surrounding liquid, of the pressure driving the piston by which this pressure is produced (that is, it is a function of the friction on the ram of the hydraulic press), and of the external pressure applied to the cylinder of the 30,000 apparatus to prevent it from bursting, the effect of this external pressure being to lengthen the 30,000 cylinder and give an apparent component to the displacement of the piston of the 100,000 piezometer. In the previous method of calculation mean values were applied for these various disturbing effects, the corrections being calculated at the extreme points on the basis of the average of many runs and the corrections for intermediate points were determined by linear interpolation. The new method of calculation was considerably more elaborate in that the three corrections were calculated in detail at every point from the various actual readings at that point. In general, the new procedure gives lower

values for the volume decrements, the decrease being confined almost entirely to the lower end of the pressure range from 25,000 to 50,000 kg/cm². The presumptive superiority of the new and more elaborate method is established by the fact that the revised method gives better agreement with the previous measurements² on the halogen compounds in the common range. These compounds had been previously measured in the range from atmospheric pressure up to 50,000 kg/cm².

A fundamental datum necessary in the calculations is the compression at 25,000 kg/cm², this being the initial pressure of these measurements. The compressions at 25,000 of the halogen compounds had been previously determined, as just mentioned, but no such information was in existence for the nitrates or AgBrO₃. Independent measurements were therefore made of the compression of these substances to 25,000 kg/cm². These were made by a new method with a new apparatus which permits rapid measurements of sufficient accuracy. The measurements will be described in the paper³ immediately following; only the results will be used here.

An improvement has been introduced in the method for determining the compression coefficient of the compressometer which permits its rapid determination, while the compressometer is mounted in the 30,000 apparatus *in situ* ready for the measurements to 100,000. The constant freshly determined by this method was a few per cent lower than in the original determination by the former method several years ago.

The difficulty on resuming measurements referred to at the end of the second paragraph of the introduction was the following. A new manipulative trick which much facilitated assembly was adopted on resumption of work; this consisted in holding one of the loose carboly plattens in position with a minute gob of wax. Many irregular results, including spurious polymorphic transitions, were traced after much time and effort to the account of the wax. At low pressures the wax dissolves in the isopentane by which pressure is transmitted and is carried in solution between the carboly platten and the grid with which the compressive stress on the piston is measured. The first few thousand atmospheres precipitates this wax in a thin film and freezes it hard; later, when the pressure in the 100,000 piezometer has reached something over 50,000, it is plastically squeezed out in the solid condition, resulting in a spuriously large

piston displacement which may simulate a transition. The remedy is scrupulously to free all internal parts of the assembly from any grease or similar substance.

Most of the substances were independently measured with two different piezometers, and the final results are the mean of two runs. Seven different piezometers were used in all, sufficient to permit definite conclusions as to the best grade of carboly to be used in their construction. Five of these piezometers were made of carboly no. 905, the grade which was found to be the most successful for the pistons in the measurements of volume changes already published up to 50,000 kg/cm². These five piezometers broke after respectively seven, twelve, seven, six, and five exposures to 100,000 kg/cm². Of the two remaining piezometers, one was of grade no. 55A and the other of grade no. 779. The first of these has at the date of writing survived 55 exposures without fracture and the second 35. The inferiority of grade no. 905 for this purpose is manifest.

EXPERIMENTAL DETAILS

The material used in these measurements was, with few exceptions, the same as that used in previous measurements either of the compressions to 50,000, or in explorations for polymorphic transitions to 50,000,⁴ and has already been described in previous papers. My old stock of single crystal NaI was exhausted and the material used here was obtained from the stock room of the Harvard Chemical Laboratory, melted in platinum, and the clear parts of the solidified product selected. NH₄Cl and NH₄Br were also fresh material from the stock of the chemical laboratory, used directly without further purification. The lead was special lead of 99.9999 per cent purity, as in the previous paper.

There follow now the pertinent details connected with the measurements of the individual substances. In the final results the mean of two independent runs was usually used, and this mean was smoothed so as to give smooth first differences over the entire pressure range from zero up, making a compromise between the present and former determinations in the common range.

In Table I certain data are given which will permit an estimate of the internal consistency of the measurements. This table gives the difference between the volume decrement at 100,000 kg/cm² as determined with either of the

TABLE I

Substance	Difference between mean $\Delta V/V_0$ at 100,000 and individual measurements	Preceding column as fraction of maximum $\Delta V/V_0$	Difference between former $\Delta V/V_0$ at 50,000 and new smoothed result
NaCl	.007	.033	+.004
NaBr	.007	.032	+.007
NaI	.011	.041	+.011
KCl	.008	.025	+.004
KBr	.014	.041	+.009
KI	.010	.029	+.007
RbCl	.000	.000	+.015
RbBr	.006	.017	+.012
RbI	.014	.035	+.016
CsCl	.005	.021	+.006
CsBr	.007	.026	+.011
CsI	.012	.041	+.005
AgCl	.000	.000	+.006
AgBr	.005	.030	+.002
AgI	—	—	+.010
TlCl	.003	.014	+.013
TlBr	.010	.045	+.014
TlI	.011	.043	+.022
NH ₄ Cl	.010	.044	+.008
NH ₄ Br	.010	.040	+.002
NH ₄ I	.017	.045	+.005
S	—	—	+.012
Pb	.0014	.010	—

two individual piezometers and the mean of the two, both as absolute volume decrement, the volume at atmospheric pressure being taken as unity, and as the fraction which the difference is of the total volume decrement at 100,000. The discrepancy between the two runs was in nearly all cases a maximum at 100,000. Of the substances listed in Table I, measurements were made on AgI with only one piezometer, and although measurements were made on NH₄I with two piezometers, the values obtained with one of them differed so much from the values previously found up to 50,000 that they were discarded and the values listed later in Table IV are based on those obtained with the other piezometer only. The difficulty with NH₄I is to a large extent characteristic of the particular material. This has a large polymorphic transition at a pressure of only a few hundred kilograms; the volume change is so large that it cannot possibly be compensated by the differential compressibility of steel and carboloy, as described in the previous paper, with the result that opportunity is afforded for the capricious trapping of liquid inside the solid resulting in too large compressions. The only way of telling whether this capricious trapping has occurred is by the internal consistency of the results; the discarding of markedly discordant runs would seem to be justified under the conditions.

The agreement of the two runs for lead and

indium is, both absolutely and fractionally, better than on the average for the salts, in spite of the fact that the absolute magnitude of the volume decrement is greater for the salts. This is without doubt a consequence of the much greater softness of the two metals, resulting in better agreement between the displacements with increasing and decreasing pressure. Measurements were made on both lead and indium in the new apparatus for 25,000. For indium there are previous measurements for comparison⁵ both in the range up to 50,000, and also to 100,000, computed by the old method. Compared with previous results, the new results are somewhat higher in the neighborhood of 50,000 than the previous results with the 50,000 apparatus, and somewhat lower than the previous results to 100,000 over the entire range. These differences are in the usual direction.

Measurements were made with only one piezometer on each of the nitrates; this was the same piezometer for all. The difference between increasing and decreasing pressure was about the same for the nitrates as for the halogen compounds, and the probable accuracy should be about the same. There are no previous measurements on the compression of nitrates to 50,000 for comparison.

Table I also lists the discrepancy between the values formerly obtained for the volume decrements at 50,000 and the values now adopted on the basis of the smoothing process over the entire range. This discrepancy is always of the same sign; that is, the value adopted here for the volume decrement is consistently greater at 50,000 than the value previously found from the measurements in the range from atmospheric to 50,000. This indicates a consistent error in the measurements somewhere. It seems probable that this consistent error is in the previous measurements to 50,000 and is connected with the fact that we are here dealing with the end of the range. It is always more difficult to get reliable measurements up to the end of the range than in the middle of the range. The sign of the discrepancy is doubtless associated with the friction, which of course is greatest at the top of the range.

The smoothed values adopted for 50,000 are also consistently less than those which would have been indicated by the measurements of this paper for the range 25,000 to 100,000. We are here dealing with the lower end of the pressure range and therefore probably with the inverse of the

effect above. That is, this method tends to give too large volume decrements at the lower end of the range and too small decrements at the upper end of the range. The accuracy of the present measurements is probably greatest in the range from 50,000 to 75,000.

DISCUSSION OF RESULTS

The numerical values of the volume decrements, in terms of the volume at atmospheric pressure as unity, are given in Tables II to VI and are plotted in Figures 1 to 4.

No elaborate discussion of these data will be attempted. Qualitatively the behavior in the range from 50,000 to 100,000 is merely a continuation of that already found in the range below 50,000. There is very little tendency for the curves of volume decrement to cross above 50,000, and the few examples of it may be due to experimental error. In a general way the atomic contributions to the volume decrements are distinctly recognizable and are the most

TABLE IV
 $\Delta V/V_0$ OF VARIOUS IODIDES

Pressure kg/cm ²	NaI	KI	RbI	CsI	AgI	TlI	NH ₄ I
10,000	.056	.065	.192 ^b	.065	.189 ^c	.050	.192 ^d
20,000	.098	.197 ^a	.235	.113	.209	.090	.230
30,000	.132	.230	.271	.151	.228	.123	.258
40,000	.160	.257	.301	.182	.246	.152	.282
50,000	.184	.279	.326	.208	.263	.177	.302
60,000	.205	.298	.346	.230	.278	.198	.320
70,000	.223	.314	.362	.249	.292	.216	.335
80,000	.239	.327	.376	.266	.305	.232	.350
90,000	.253	.338	.388	.281	.317	.245	.363
100,000	.266	.348	.398	.294	.328	.256	.376

^a Transition at 18,200; $\Delta V/V_0$'s at transition .105 and .190

^b Transition at 4,050; $\Delta V/V_0$'s at transition .035 and .161

^c Transition at 3,000; $\Delta V/V_0$'s at transition .011 ± & .174

^d Transition at 560; $\Delta V/V_0$'s at transition .003 ± & .143

TABLE V

$\Delta V/V_0$ OF VARIOUS NITRATES

Pressure kg/cm ²	NaNO ₃	KNO ₃	RbNO ₃	CsNO ₃	AgNO ₃	TlNO ₃	NH ₄ NO ₃
10,000	.034	.138 ^b	.043	.045	.044 ^a	.037	.050
20,000	.062	.169	.079	.083	.077	.068	.086
30,000	.086	.196	.109	.115	.103	.095	.115
40,000	.107	.219	.135	.142	.126	.118	.140
50,000	.127	.238	.157	.165	.146	.137	.162
60,000	.154 ^a	.255	.175	.183	.162	.152	.180
70,000	.167	.268	.190	.198	.176	.165	.194
80,000	.180	.280	.202	.210	.188	.176	.206
90,000	.191	.289	.211	.219	.198	.185	.215
100,000	.201	.297	.219	.226	.206	.194	.222

^a Transition at 55,000; $\Delta V/V_0$'s at transition .136 and .147

^b Transition at 3,650; $\Delta V/V_0$'s at transition .023 and .113

^c Transition at 9,500; $\Delta V/V_0$'s at transition .030 and .043

TABLE II

$\Delta V/V_0$ OF VARIOUS CHLORIDES

Pressure kg/cm ²	NaCl	KCl	RbCl	CsCl	AgCl	TlCl	NH ₄ Cl
10,000	.038	.048	.188 ^b	.048	.021	.038	.049
20,000	.068	.084	.219	.086	.040	.071	.082
30,000	.093	.223 ^a	.246	.118	.058	.099	.109
40,000	.115	.244	.270	.144	.074	.123	.133
50,000	.135	.262	.292	.166	.090	.144	.154
60,000	.152	.277	.311	.184	.104	.162	.172
70,000	.168	.290	.327	.199	.117	.177	.188
80,000	.183	.302	.341	.212	.129	.191	.202
90,000	.197	.312	.353	.223	.140	.202	.215
100,000	.210	.321	.364	.233	.165 ^c	.213	.227

^a Transition at 20,060; $\Delta V/V_0$'s at transition .085 and .197

^b Transition at 5,000; $\Delta V/V_0$'s at transition .030 and .170

^c Transition at 90,000; $\Delta V/V_0$'s at transition .140 and .156

TABLE III

$\Delta V/V_0$ OF VARIOUS BROMIDES

Pressure kg/cm ²	NaBr	KBr	RbBr	CsBr	AgBr	TlBr	NH ₄ Br
10,000	.043	.055	.188 ^b	.053	.022	.043	.049
20,000	.078	.199 ^a	.221	.095	.041	.077	.088
30,000	.107	.229	.250	.130	.059	.106	.120
40,000	.132	.254	.275	.160	.075	.131	.147
50,000	.153	.274	.297	.186	.091	.152	.170
60,000	.171	.291	.315	.208	.106	.170	.189
70,000	.186	.305	.330	.227	.120	.186	.205
80,000	.199	.317	.343	.243	.133	.200	.219
90,000	.211	.327	.354	.258	.157 ^c	.212	.232
100,000	.222	.336	.364	.272	.169	.223	.244

^a Transition at 18,400; $\Delta V/V_0$'s at transition .088 and .193

^b Transition at 4,600; $\Delta V/V_0$'s at transition .033 and .166

^c Transition at 86,000; $\Delta V/V_0$'s at transition .141 and .152

TABLE VI

$\Delta V/V_0$ OF FOUR MISCELLANEOUS SUBSTANCES

Pressure kg/cm ²	AgBrO ₃	Pb	In	S
10,000	.027	.0215	.0240	.083
20,000	.050	.0410	.0442	.131
30,000	.071	.0587	.0619	.163
40,000	.088	.0747	.0781	.188
50,000	.104	.0892	.0932	.208
60,000	.117	.1024	.1072	.225
70,000	.129	.1145	.1202	.240
80,000	.138	.1255	.1324	.253
90,000	.147	.1356	.1439	.264
100,000	.154	.1449	.1549	.274

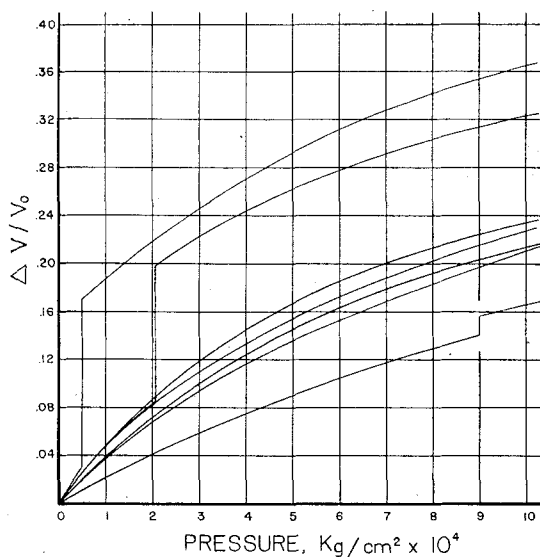


FIGURE 1. The volume decrements of the chlorides as a function of pressure. The order of the curves at 100,000 kg/cm², reading from top down, is: Rb, K, Cs, NH₄, Tl, Na, and Ag.

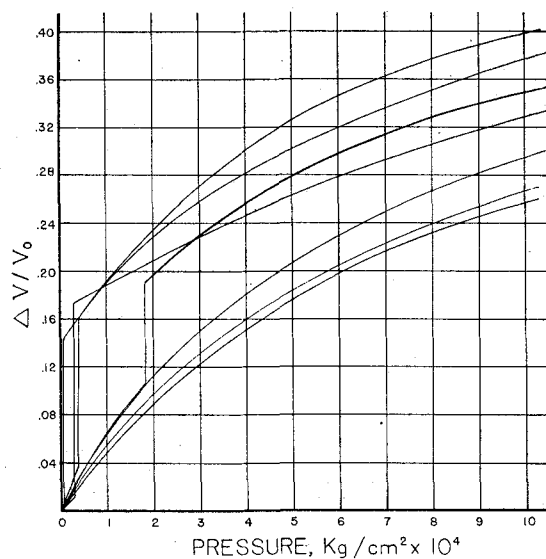


FIGURE 3. The volume decrements of the iodides as a function of pressure. The order of the curves at 100,000 kg/cm², reading from top down, is: Rb, NH₄, K, Ag, Cs, Na, and Tl.

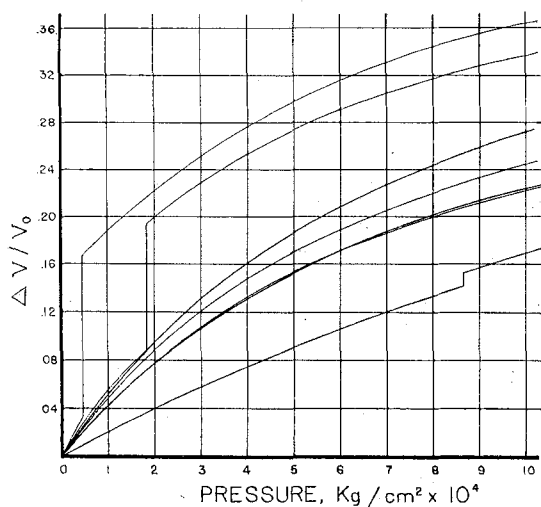


FIGURE 2. The volume decrements of the bromides as a function of pressure. The order of the curves at 100,000 kg/cm², reading from top down, is: Rb, K, Cs, NH₄, Tl, Na, and Ag.

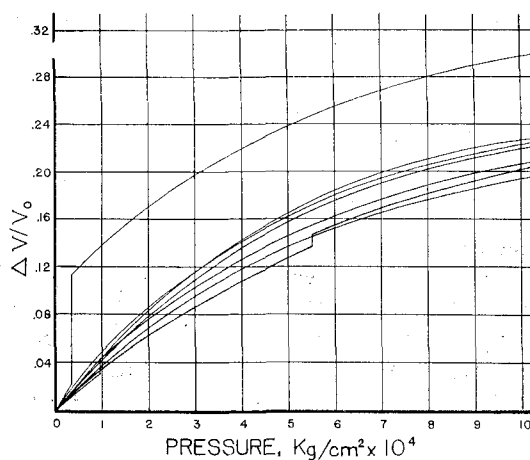


FIGURE 4. The volume decrements of the nitrates as a function of pressure. The order of the curves at 100,000 kg/cm², reading from top down, is: K, Cs, NH₄, Rb, Ag, Na, and Tl.

important factor in determining compression at these high pressures. Disregarding the effect of polymorphic transition, and other things being equal, the compression increases on passing from chloride to bromide to iodide. The nitrates are about as compressible as the corresponding chlorides. With regard to the atom of the metal, the compression increases in the series sodium, potassium, rubidium, and caesium. The compounds of thallium in general show about the same compression as the corresponding sodium compounds, and the compounds of ammonium the same as those of potassium or rubidium. The compounds of silver are distinctly less compressible than those of any of the other metals just enumerated.

The falling off in compressibility with increasing pressure may be exhibited by comparing the volume decrement for the interval atmospheric to 50,000 with that for the interval 50,000 to 100,000. These values are listed in Table VII,

TABLE VII
COMPARISON OF VOLUME DECREMENTS AT LOW AND HIGH PRESSURES

Substance	$\Delta V/V_0$ 0-50,000	$\Delta V/V_0$ 50,000-100,000	Ratio
NaCl	.135	.075	1.80
CsCl	.166	.067	2.48
TlCl	.144	.069	2.08
NH ₄ Cl	.154	.073	2.11
NaBr	.153	.069	2.22
CsBr	.186	.086	2.16
TlBr	.152	.071	2.13
NH ₄ Br	.170	.074	2.29
NaI	.184	.082	2.24
CsI	.208	.086	2.42
TlI	.177	.079	2.24
RbNO ₃	.157	.062	2.53
CsNO ₃	.165	.061	2.71
TlNO ₃	.137	.057	2.41
NH ₄ NO ₃	.162	.061	2.66
AgBrO ₃	.104	.050	2.08
Pb	.089	.056	1.60
In	.093	.062	1.52
S	.208	.066	3.14

and are plotted in Figure 5. Figure 5 clearly shows the well known fact that in general the greater the absolute compressibility of a substance the more rapid its relative decrease of compressibility with increasing pressure. It would, in fact, be surprising if something like this were not approximately the case, this being a geometrical consequence of the fact that an upper limit to the volume decrement is unity, negative volumes being meaningless. Figure 5 also brings out another general tendency, namely that other things being equal the substance with the more complicated atomic structure experiences the

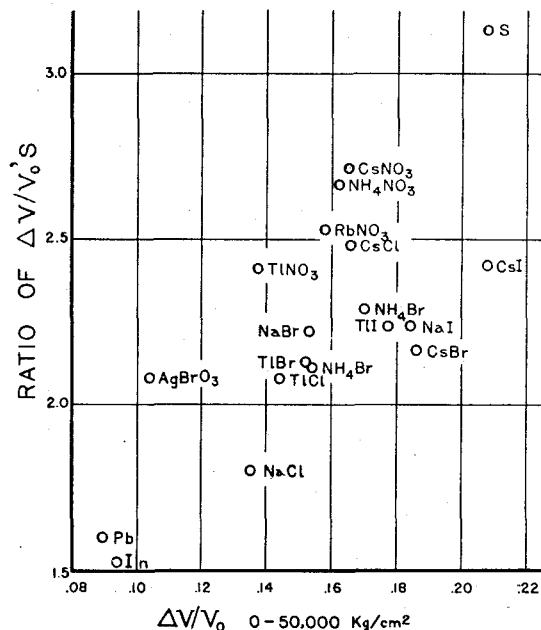


FIGURE 5. The ratio of the volume decrement 0 to 50,000 kg/cm² to the decrement 50,000 to 100,000 kg/cm² plotted against the volume decrement 0 to 50,000 kg/cm².

greatest relative decrease of compressibility with increasing pressure. This again would be expected on rather general grounds. The more complicated structure may be expected to have more internal vacancies or more "slack" to be taken out by the initial application of pressure. In this respect the solid with complicated structure approaches more closely to a liquid, in which there is a large amount of internal slack and a rapid initial decrease of compressibility with increasing pressure.

Only three examples of new polymorphic forms were found: NaNO₃, AgCl, and AgBr. It is perhaps surprising that not more were found, although in explanation it is to be commented that already at low pressures most of these substances must have already acquired about their maximum simplicity and symmetry of structure. It is probable that the transitions of AgCl and AgBr are from the face centered lattice, which is the stable form at atmospheric pressure, to the body centered lattice, in analogy with the transitions of the potassium and rubidium halides. It is of some interest that no transition was found for the sodium halides. A formal extrapolation of the results already found for the halides of rubidium and potassium might lead to the expectation of transitions of the sodium salts in the

new range. However, a careful calculation of the probable energy relations by Dr. Jacobs⁶ has indicated that the probability of the transition fades out of the picture somewhere between potassium and sodium, and these experimental results support his conclusion.

There does not seem to be any simple method of guessing what the type of transition is for NaNO_3 , the nitrates exhibiting a number of possibilities in the way of transition.

On the basis of previous measurements⁷ it might have been expected that transitions would have been found for rubidium, caesium, and silver nitrates. However, if the previous work is consulted it will be found that the transition of CsNO_3 , which occurs in the neighborhood of 30,000, was getting so sluggish that it could not be picked up even with the former apparatus at temperatures below 125° . RbNO_3 similarly, which according to the former measurements has a transition at room temperature in the neighborhood of 17,000 kg/cm^2 , is nevertheless so sluggish at this temperature that the band of indifference was 14,000 kg/cm^2 wide. It is therefore probable that the transitions of both CsNO_3 and RbNO_3 were totally suppressed in this work, and that the volume decrements listed here apply to the ordinary modifications, compressed far into their regions of thermodynamic instability. AgNO_3 , on the other hand, according to previous work has a couple of transitions between 30,000 and 45,000 which might have been picked up. It is to be remarked, however, that the first of these transitions, from II to III, is sluggish, and may have been suppressed, the much greater speed and the much smaller quantity of substance in these experiments both being factors favoring

suppression of the transition. It is true that the second transition found before, from III to IV, was not sluggish at room temperature, but if the transition from II to III had not previously occurred we would be concerned at high pressures with the transition II to IV, instead of III to IV, and there is no basis for judging whether the former transition would be sluggish or not. The probability is, therefore, that all transitions were suppressed, and that the volume decrements of Table V are the decrements for phase II. Taken altogether, these results give increased probability to the correctness of Tammann's thesis, for which there was already much favorable evidence, that the probability of transition to the thermodynamically stable modification passes through a maximum and then decreases as pressure increases along an isotherm away from the point of reversible transition.

It is a pleasure to acknowledge the skillful assistance of my mechanic Mr. Charles E. Chase.

RESEARCH LABORATORY OF PHYSICS,

Harvard University, Cambridge, Mass.

REFERENCES

- ¹ P. W. Bridgman, *Phys. Rev.* 60, 351-354, 1941.
Proc. Amer. Acad. 74, 425-440, 1942.
- ² P. W. Bridgman, *Proc. Amer. Acad.* 74, 21-51, 1940.
- ³ P. W. Bridgman, *Proc. Amer. Acad.* (to be supplied in proof)
- ⁴ P. W. Bridgman, *Proc. Amer. Acad.* 72, 45-135, 1937.
- ⁵ Reference 2, p. 31, and second reference under 1, p. 434.
- ⁶ R. B. Jacobs, *Phys. Rev.* 54, 468-474, 1938.
- ⁷ P. W. Bridgman, *Proc. Amer. Acad.* 51, 581-625, 1916, and also reference 4, pp. 86 and 87.

THE COMPRESSION OF SIXTY-ONE SOLID SUBSTANCES TO 25,000 kg/cm², DETERMINED BY A NEW RAPID METHOD

By P. W. BRIDGMAN

Presented Oct. 11, 1944.

Received Oct. 17, 1944.

CONTENTS

INTRODUCTION.....	9
APPARATUS AND METHOD.....	9
DETAILED RESULTS.....	14
1. Elements.....	14
Thallium.....	14
Arsenic.....	15
Cadmium.....	15
Indium.....	16
Lead.....	16
Carbon (graphite).....	17
2. Inorganic Salts.....	17
A. Univalent Nitrates.....	17
B. Certain Halogenates and Perhalogenates.....	18
3. Organic Solids.....	19
A. Definite Compounds.....	19
B. Synthetic and Natural Rubbers.....	21

INTRODUCTION

In the following, a new apparatus is described by which the cubic compression of solid substances may be rapidly determined in the pressure range from atmospheric to 25,000 kg/cm² at room temperature, and the results obtained with it are presented for 6 elements, 26 salts, 15 organic solids, and 14 artificial and natural rubbers. The apparatus operates on about 0.1 cm³ of material, requires two hours or less for the complete run, including assembly, and disassembly ready for the next run, with 30 readings uniformly spaced over the pressure range. The individual points lie smoothly on a curve within 1 part in 2000 of the initial volume or better, depending on the nature of the material, with correspondingly greater accuracy in the mean curve.

APPARATUS AND METHOD

The method is a development of the method previously used¹ for the determination of compressions and polymorphic transitions to 50,000 kg/cm². By this method, the material, enclosed in a sheath of a soft metal, usually indium, in

order to ensure that the stress should be approximately hydrostatic, was placed in a steel container with an external conical surface fitting a steel sleeve, so designed that when the internal pressure increased the external pressure simultaneously increased, thus resisting the tendency to fracture. The volume compression was determined from the motion of the piston with which pressure was generated. The reduction of the measured piston displacement to volume decrement involved a number of corrections, which were somewhat in doubt because of friction and hysteresis. The pressure range was so high that the containers were subject to slow creep in dimensions, which always eventually resulted in fracture after anywhere from 10 to 100 applications of pressure.

The new and modified method in the first place restricts the pressure to one half the former range, with the object of avoiding creep and fracture and permitting the indefinite use of the apparatus. This appears to have been successful, and to date some 200 applications of 25,000 have been made with no fracture of any part of the apparatus and no measurable change of any dimension. The corrections, furthermore, are much simplified and minimized by so designing the apparatus that the change of cross sectional area of the container under internal pressure is small, leaving as the one most important outstanding correction one for the longitudinal compression of the carboloy pistons.

The apparatus is shown in detail in Figure 1. It is mounted on the same "tandem" hydraulic press that was previously used in the measurements to 50,000. This press comprises in the first place a 6-inch plunger, by which the pressure vessel is pushed as a whole into its conical sleeve so as to generate the external pressure resisting fracture. Riding on the 6-inch piston is a 3.5 inch piston by which pressure is exerted on the inside of the high pressure chamber. The core of the high pressure vessel itself is made of car-

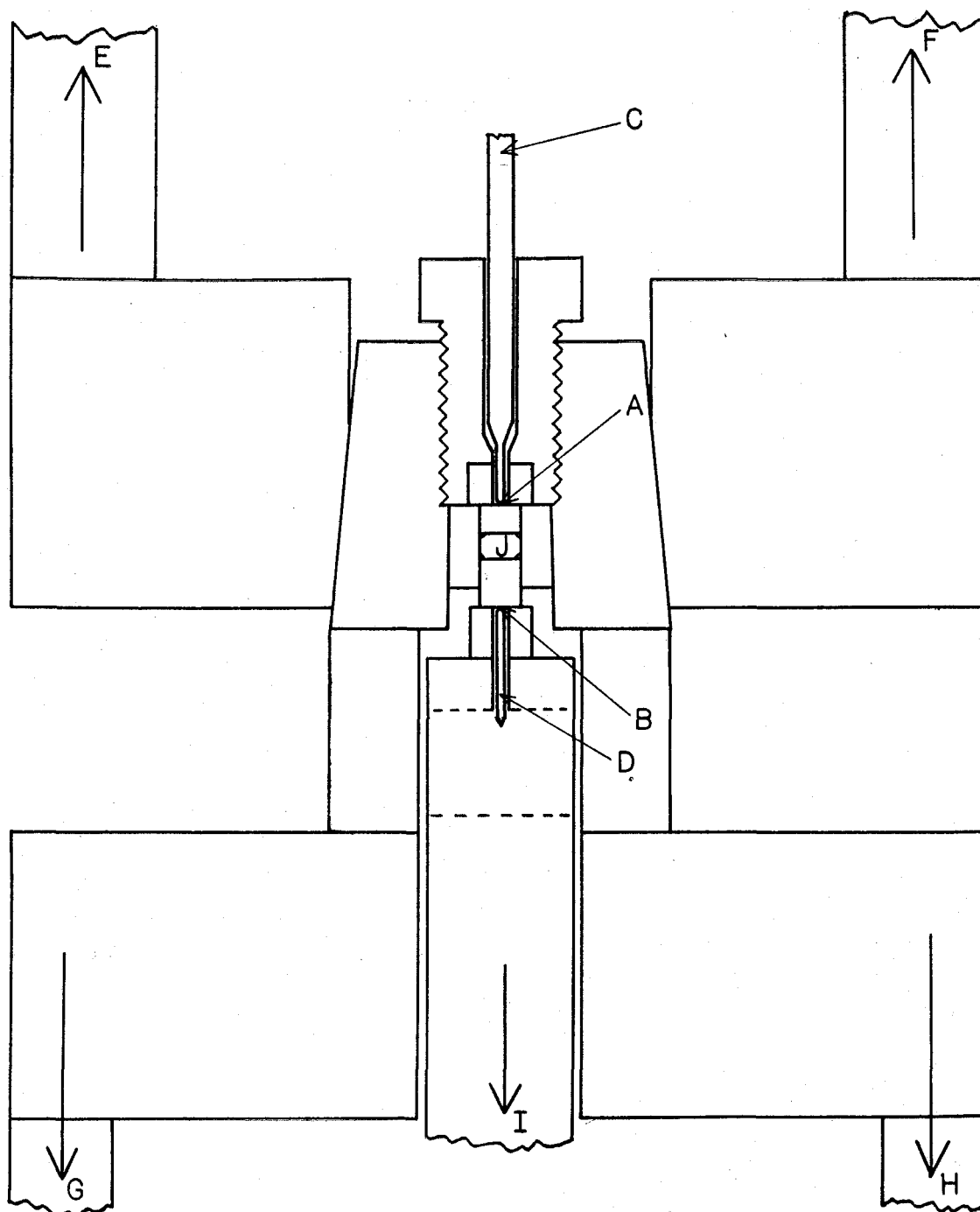


FIGURE 1. General assembly of compressibility apparatus. The charge whose compression is to be measured is shown at *J*. The relative motion between the points *A* and *B* is taken off by means of the feeler rods *C* and *D* and a yoke and 1/10,000 gauge (not shown). The compression member *I* is actuated by the ram of the 3.5 inch press (not shown), and the conical vessel is pushed into its supporting collar by means of *G* and *H* actuated by the ram of the 6 inch press (not shown). The members *E* and *F* transmit the total thrust to the top platten of the tandem press (not shown).

boloy, grade no. 905, 0.47 inches long and 0.63 inches outside and 0.25 inches inside diameter, ground with a taper of 0.010 inches on its total length, and forced into the surrounding conical steel block to such an extent as to expand the inside of the steel block by 0.004 inch. In operation, the two pistons of the tandem press are both directly connected to the single source of hydraulic pressure, instead of being connected through a multiplying mechanism by which the pressure on the two pistons was previously maintained at a fixed ratio different from unity. In this way operation was simplified and error from friction in the multiplier avoided. The dimensions and angle of the steel block into which the carboloy core was forced were so chosen that the pressure on the outside of the carboloy was automatically maintained at about one quarter of the internal pressure. Under these conditions the internal expansion of the carboloy container keeps pace with the small lateral expansion of the carboloy piston so that the crack around the piston remains of constant size, and the tendency to leak, or the friction with the piston, does not increase. It is to be remarked that apart from the other improvements in design, merely by making the core of carboloy the distortions were cut down to one-third of what they would have been with steel, because of the higher elastic constants of carboloy.

The charge, whose volume compression is to be measured, occupies the central part of the carboloy core, and is approximately 0.125 inches long and 0.250 inches in diameter. These dimensions are a compromise. The longer the charge, the greater the change in length for a given change of pressure, that is, the greater the sensitivity, but on the other hand, the greater the length, the greater the friction and the greater the error from difference between displacements with increasing and decreasing pressure. Theoretically, the ratio of the frictional force to the total compressing force may be made vanishingly small by indefinitely reducing the ratio of the surface on which the friction acts to the area on which the total compressing force acts, that is, by making the charge in the form of an indefinitely thin disc. But in this case the displacements which measure the volume compression also become vanishingly small. The dimensions just mentioned were chosen after some trial as giving a reasonable compromise.

The charge is compressed between two cylindrical carboloy blocks, the upper block in Figure 1

being held rigidly in place against a carboloy anvil inserted into the steel retaining screw, and the other block constituting the compressing piston. The relative displacement of the ends of these two blocks was measured by steel feeler rods reaching in through axial holes in the supporting carboloy anvil blocks as shown, and connected with an Ames 0.0001 inch jeweled gauge. The gauge had been specially selected by the manufacturers from a large number because of its negligibly small calibration errors. The relative displacement, measured in this way, is, except for the distortion of the blocks, the change of length of the charge, and from this, if the change of cross section of the charge is known, the volume decrement of the charge may be at once obtained. The distortion of the blocks consists primarily of a shortening, but superposed on this the faces in contact with the charge may not remain flat. With the dimensions chosen the effect of any warping of the plane ends of the blocks appears to be negligibly small, but the warping becomes relatively more important as the thickness of the charge is made smaller, and eventually would impose a limit, entirely apart from the effect of the decrease of the absolute magnitude of the measured displacement as the disc becomes thinner.

With the actual dimensions of the charge, 0.25 inch diameter and 0.125 inch long, the friction on the walls of the carboloy container generated by the longitudinal motion connected with the compression would have been excessive for most solid substances, so that it was necessary to surround the charge with a sheath of indium, as in previous work. The indium is so soft that it will support only an approximately hydrostatic pressure, thus producing the proper stress system on the charge and at the same time eliminating most of the friction on the walls. The indium, in weighed amount, usually in the neighborhood of 0.140 gm., was formed into a cup shaped sheath in place in the carboloy container with a suitably shaped forming tool, the thick bottom of the cup being in contact with the moving carboloy piston, and the thin edge of the cup being in contact with the stationary carboloy block. (Figure 2.) The solid to be measured was, if originally in the form of powder, formed into a conical slug by compression in a split mold, or, if it was coherent enough, was turned in the lathe from the massive block to such dimensions as to fit the inside of the indium cup. The indium was prevented from leaking past the carboloy pistons

by thin conical steel rings as indicated in the figure. These rings were made initially about 0.001 inch too large in diameter, but because of their thinness they could be seated in position with the exercise of only a moderate force. They were effective in preventing any detectable leak. The quantity of steel in the sealing rings was controlled by weighing, the weight being about 0.015 gm. each. A slight correction was applied for the compression of the rings.

Pressure was applied to the two pistons of the tandem press through the medium of ordinary

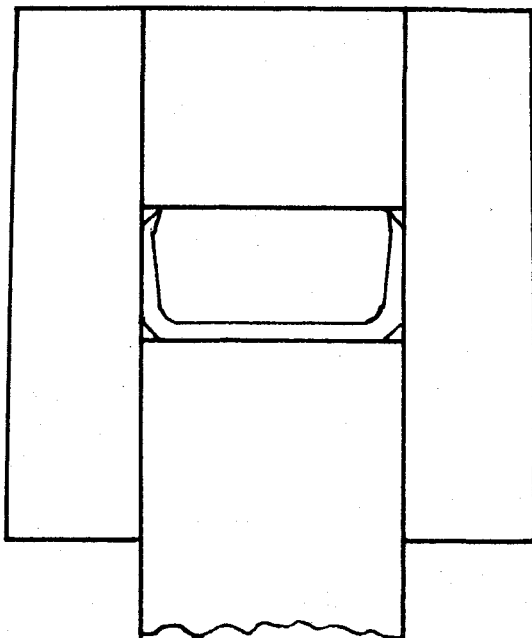


FIGURE 2. Detail of compression sample, showing the sample in the cup shaped indium sheath with the conical closure rings.

machine oil and the conventional hand pump. The feeding pipe passed through a dead weight free piston gauge in series between pump and press. Freedom of flow through the connecting pipe between free piston gauge and press was lowered by plugging the pipe with a wire of diameter only slightly less than that of the pipe. In this way any pulses of pressure originating in the pumping or changing of weights on the gauge were avoided. This was necessary because pressure must increase or decrease monotonically in order to regularize what small friction effects there are and to justify eliminating them by taking the average of readings with increasing and decreasing pressure.

After setting up the apparatus, a preliminary

application of the maximum pressure, about 26,500 kg/cm², was made in order to consolidate the contents. The initial zero may, depending on the degree of success in getting rid of all voids in the initial filling, be displaced by a considerable amount by this first application, but the piston reading at the first maximum of pressure seldom if ever differed by more than 0.0001 inch from the reading on the second maximum, showing the effectiveness of the preliminary application of pressure in removing all voids and bringing to a steady state. After the seasoning application, pressure was increased in steps of approximately 2,000 kg/cm² by the addition of weights to the piston of the dead weight gauge, and the corresponding readings made on the Ames gauge. Within the limits of comfortable operation of the apparatus, there were in general no time effects, but after every increase of pressure there was no creep in piston displacement, at least after the lapse of the 20 or 30 seconds after the piston gauge had reached equilibrium which was necessary before a reading could be made. Thermal effects are of course to be expected after every increase of pressure; the rapid attainment of equilibrium here is a consequence of the small size of the apparatus and its good thermal conductivity. The only point at which there was perceptible creep was at dead zero, where the elastic recovery imparted by the remnants of shape of the charge might result in the gradual development of voids. The dead zero reading was not used in the calculations, the first point being put at about 250 kg/cm². The actual process of making the run, increasing and decreasing pressure in steps of 2,000 kg/cm² and recording the readings required something of the order of 20 minutes. The rest of the operations of assembly, disassembly, plotting the points, etc. could be done without undue haste, if there were no unusual hitches, so as to make the total time of a run about one and one half hours.

It was intended to make the method differential like its predecessor. At first, measurements on a given substance were compared with blank runs in which the substance was replaced with an equivalent amount of gold, and the compression computed by difference, assuming the compression of gold known. The blank runs showed such a high degree of uniformity, however, that they were eventually discarded, their final function being merely to give the compressive distortion of the carboly pistons. It turned out that the correction for the change of cross section

of the carboly core was negligible, so that the final result could be obtained directly from the measured displacement, making one subtractive correction for the shortening of the pistons, another for the compression of the indium sheath, which was known in terms of the weight and the previous measurements of the compression of indium, and a very small correction for the compression of the steel sealing rings which was so nearly constant that it could be incorporated into the correction for the shortening of the pistons. The ratio of the corrected displacement to the initial effective length of the charge then gives at once the fractional change of volume, the relative change of cross section, as just mentioned, being negligible.

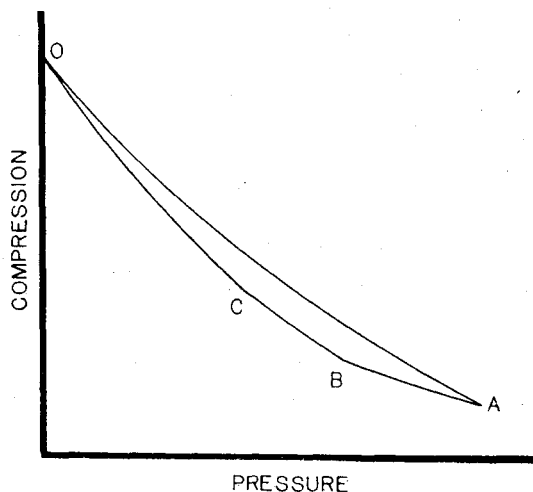


FIGURE 3. Typical compression curve.

The method as just described was arrived at only after a good many exploratory attempts to develop a method for the rapid measurement of the compressibility of solids to high pressures which should exploit the great ease with which rapid measurements of small displacements can be made with the jeweled Ames 0.0001 inch gauge, and the possibility of getting very high stresses in small regions of carboly apparatus suitably supported by the surrounding parts. It is possible to reach pressures of more than 100,000 kg/cm² in carboly apparatus similar to my shearing apparatus, and to measure the displacements of the pistons in compressing a very thin disc of material. Or, by making the disc somewhat thicker and compressing into a shallow cavity excavated in the face of a carboly block, greater sensitiveness can be attained, but not such high pressures. None of the many other

schemes tried, however, was encouraging from the point of view of accuracy and reproducibility, the distortions in the carboly corresponding to dishing of the flat face of the piston in the apparatus above being too large a fraction of the total effect.

In Figure 3 is shown a typical curve of displacement versus pressure. The branch with increasing pressure, from *O* to *A*, is typically perfectly smooth, but the branch with decreasing pressure consists of three more or less distinct portions. The last part of the return excursion, from *C* to *O*, is smooth, and the difference of displacement compared with the ascending branch is approximately proportional to the pressure. The obvious interpretation of this portion is that the difference between the two branches is due to friction, which would be expected to be proportional to pressure, and that the proper mean to take is the arithmetic mean of the displacements with increasing and decreasing pressure. Before reaching *C* on releasing pressure the readings run through a stretch from *B* to *C* in which the difference between readings with increasing and decreasing pressure is approximately constant. The first portion of the return path, from *A* to *B*, is merely a connecting link, without special significance, in which the full reverse motion of all parts of the charge gets progressively established. The interpretation of the constant difference between ascending and descending branches between *B* and *C* is suggested by my experiments on shearing under pressure.² Here it was found that when one solid is forced to slide over another under continually increasing normal pressure, at first the force resisting motion is an ordinary frictional force, arising from surface slip, and is proportional to the normal pressure, but when the normal pressure reaches such a value that the frictional force becomes equal to the stress required to produce internal plastic flow, surface slip ceases, and further relative motion is accomplished by internal plastic flow, the force being to a first approximation, and for not too wide pressure intervals, independent of pressure. This phenomenon was taken to be the interpretation of the constant difference between the two branches from *B* to *C*, and consequently the corrected mean curve between *B* and *C* is to be taken as half way between the ascending and descending curves, or, in this case, the curve for increasing pressure corrected by a constant additive displacement. Obviously the corrected curve between the pressure at *B* and the maximum at *A*

cannot be the mean of the displacements with increasing and decreasing pressure. If the above interpretation is correct, then the corrected curve between *B* and *A* is the curve for increasing pressure corrected by the same constant additive term as was used between *A* and *B*, neglecting the change with pressure of internal plastic flow stress, which previous work indicates is justified for this range of pressure. The data to be given in the following were obtained by correcting the measurements in this way.

The magnitude of the difference between ascending and descending curves is a strong function of the character of the material being compressed. It is least for soft metals. For indium the maximum difference in displacement between ascending and descending branches was only 0.0001 inch, which is of the order of one per cent of the maximum displacement for this metal. Probably only a small part of this difference arises from internal friction in the indium, but rather arises from friction in other parts of the apparatus. Friction would be expected at the two pistons of the tandem press, and on the outside of the conical block of steel. The pistons of the press were specially treated to reduce friction to a minimum by making the packing thin; the conical steel block was lubricated in the conventional way with 0.002 inch lead foil smeared on both sides with a mixture of graphite, glycerine, and water. An upper limit to the friction from all sources except internal friction in the charge itself would seem from these experiments with indium to be 0.5 per cent. From a minimum difference of 0.0001 inch between ascending and descending branches for indium, the difference might rise to 0.001 inch, ten times as much. Ten times as much does not mean, however, ten times as great proportional error, because the absolute values of displacement were also larger for these substances. It was very seldom that the difference between ascending and descending branches reached as much as 5 per cent of the maximum displacement, or a discrepancy of 2.5 per cent between the mean and either ascending or descending branch. Of course the accuracy of the mean itself should be much higher than this. Even so, it perhaps requires a word of comment as to why there should be as much discrepancy as this. If the indium sheath functions as intended and maintains a hydrostatic pressure on the charge inside it, one might perhaps at first expect no such effect at all, since hydrostatic compression is frictionless and with-

out hysteresis. This applies, however, only to homogeneous material, isotropic or not. The material of these experiments was in most cases highly non-homogeneous, being compressed from powdered or granular material. If the material is non-cubic in its crystal structure, the linear compressibility is in general different in different directions, and the grains change shape under an external hydrostatic pressure. Therefore in a haphazard aggregate of grains of non-cubic material an external uniform hydrostatic pressure produces in general relative motion, with plastic flow and slip of one grain on another and hysteresis. In support of this, the difference between ascending and descending branches was comparatively small for cubic materials, even if they might be of comparatively high mechanical strength. For example, the difference between different branches for NaCl was only about one-third as much as for naphthalene, although to ordinary mechanical stresses the latter is much more deformable than NaCl.

The preliminary work in developing the apparatus and technique of measurement was done with NaCl-clear single crystal stock. The presumptive accuracy of the method can be estimated from a comparison of the results obtained in this apparatus with previous results determined in the pressure range up to 50,000 kg/cm², as shown in Table I.

TABLE I
COMPRESSION OF NaCl

Pressure kg/cm ²	$\Delta V/V_0$	
	Present Measurements	Previous Measurements to 50,000
5,000	.0189	.0192
10,000	.0362	.0365
15,000	.0520	.0523
20,000	.0664	.0664
25,000	.0795	.0798

DETAILED RESULTS

1. *Elements.* Occasion was taken to fill in certain gaps in the compressions of the elements which for one reason or another had not been previously measured to pressures high enough to give an indication of the change of compressibility with pressure. The new values are collected in Table II.

Thallium. This has not been previously measured in the range below 25,000. Thallium crystallizes in the hexagonal system so that a complete description of the behavior under pressure demands a measurement of the linear

TABLE II
 COMPRESSION OF ELEMENTS

Pressure kg/cm ²	Thallium	Arsenic	Cadmium	$\Delta V/V_0$ Indium	Lead			Ceylon Graphite
					These measurements	From linear compression	Powder	
5,000	.0130	.0119	.0100	.0127	.0110	[.0112]	.0170	.0138
10,000	.0251	.0221	.0194	.0241	.0215	[.0219]	.0323	.0260
15,000	.0367	.0309	.0283	.0347	.0315	[.0321]	.0460	.0366
20,000	.0476	.0385	.0368	.0445	.0411	[.0419]	.0583	.0458
25,000	.0577	.0447	.0449	.0537	.0504	[.0513]	.0718	.0535

compression parallel and perpendicular to the hexagonal axis of the single crystal. I had hoped when making the low pressure measurements to be able to operate with the single crystal, but have not yet successfully prepared single crystals of this metal, the difficulty with the method which I had previously used for the other low melting metals being that thallium attacks the glass container. The volume compression could now, however, be so easily obtained with the new apparatus that it seemed worth while, even if the results would not be complete. The material was some highly purified metal which I had inherited from Professor T. W. Richards, used by him in his measurements of compression in the range up to 500 kg/cm². Thallium is so soft that it could be compressed directly into the carboloy container without the necessity for a sheath of indium. The difference of displacements with increasing and decreasing pressure was at most only 2 per cent of the maximum displacement. The compressibility at atmospheric pressure, extrapolated from these measurements, was found to be 2.7×10^{-7} , against the value of Richards and White³ of 2.78 in the range up to 500. The agreement is within the sensitiveness of the readings, and again gives presumptive evidence of the reliability of this new method.

Measurements have already been presented⁴ for the compression of thallium in the 100,000 apparatus, the range of those measurements being from 25,000 to 100,000. At that time, the fiducial change of volume at 25,000, necessary for the calculations, had not been determined, and it was arbitrarily assumed that the volume decrement was the mean between that of lead and indium, or 0.052. The fiducial volume decrement at 25,000 is now found by direct measurement to be 0.0577. This will permit a re-evaluation of the compressions to 100,000, which will be given in a following paper.

Arsenic. This, like thallium, does not crystallize in the cubic system; it is furthermore known

to be highly non-isotropic. The material was highly purified single crystal stock prepared by Dr. W. E. Danforth a number of years ago, the same material as that used in a detailed study of the many anomalies of linear compressibility and electrical resistance of this highly abnormal metal.⁵ The sample used in the present measurements was composed of a number of single crystal grains compressed together in haphazard orientation. The regular indium sheath was used. Considerable difference between readings with increasing and decreasing pressure was to be expected because of the mechanical hardness and high non-isotropy. The maximum difference between displacements with rising and falling pressure was 10 per cent of the maximum displacement. The average should be fairly good, because rising and falling curves were smooth, with no trace of the anomalies previously found in the linear compression, which indeed was not to be expected because those anomalies were on too small a scale. The initial compressibility at atmospheric pressure, extrapolated from the present measurements, is 2.5×10^{-6} . This is to be compared with the value 3.2×10^{-6} deduced from my previous measurements of linear compression in different directions, and the value of Richards⁶ of 4.4×10^{-6} in the pressure range below 500 kg/cm². The explanation of the latter high value is doubtless the formation of voids because of unequal compressibility in different directions.

Cadmium. This material also does not crystallize in the cubic system, so that a complete description of the phenomena of compression demands a measurement of the linear compression of the single crystal in different directions. The measurement of linear compression, however, encounters an unusual complication, because in the single crystal form there are polymorphic transitions at comparatively low pressures,⁷ and on passing through them the single crystal form is lost, so that measurements of

linear compression cannot be carried above the transition pressure. The average volume compression as measured here presents, therefore, only a partial picture, but seemed to be worth while in the absence of other information.

The material was spectroscopically pure, for which I am indebted to Dr. H. M. Cyr of the New Jersey Zinc Co. It was mechanically soft enough so that it could be used without the indium sheath without undue friction. The initial compressibility at atmospheric pressure, extrapolated from the volume decrements given in the table, is 2.06×10^{-6} , which is to be compared with 2.21×10^{-6} obtained indirectly from the measured elastic constants of the single crystal.⁷ The anomalies previously found in the linear compression would not be expected to be detectible with the present method.

Indium. The reason for making new measurements on this metal was the continued use of its compression in correcting the other measurements. The material was probably not of specially high purity; it is part of the same stock that has been used in all my other work. The new measurements should be better than any others hitherto made; it has already been mentioned that friction and hysteresis were reduced to a very low value. The deviation of the new values from those last published⁸ for the range up to 100,000 kg/cm² is not great; at 10,000, 0.241 now against 0.023 previous; and at 20,000, 0.0445 now against 0.045 previous. The new values to 25,000 have afforded the basis for improved measurements to 100,000 which have been communicated in the immediately preceding paper.

Lead. The only previously published values to high pressures⁹ reach to 45,000; these measurements were rough, being among the earliest obtained by this general method, before the later refinements had been worked out.

The material was 99,9999 per cent purity lead, which I owe to the kindness of Dr. Phillips, to whom it had been sent by the Federated Metals Corporation, 120 Broadway, New York City. This material is particularly well adapted to the new method because of its mechanical softness. It was used without the indium sheath; the maximum difference between ascending and descending readings was 0.0002 inch. The values now found are to be compared with the previous values in the range to 45,000 as follows: at 10,000, 0.0215 now against 0.023 previous; and at 25,000 0.0504 now against 0.050 previous.

In addition to these values, measurements as

yet unpublished were made in 1939 by the method of linear compression with sliding potentiometer wire to 30,000 kg/cm², using in the calculations recently redetermined values for the linear compressibility of iron. They should have the highest accuracy that I have yet reached. A more detailed account will be published of this work when I have had opportunity to add more materials, which at present embrace only lead, aluminum, copper, and pure iron from two sources. In the meantime, the results by this method are given in Table II for comparison, enclosed in brackets. The absolute values of the presumably more accurate method are consistently higher than by the method of this paper. It is significant, however, that the rate of decrease of compressibility with pressure by the two methods is the same to the limit of significant figures. It is to be emphasized that these two methods are quite independent of each other.

On the basis of these new measurements the compression of lead has recently been measured up to 100,000; the results are given in the preceding paper.

In connection with other measurements occasion arose to measure the compression of finely powdered lead. It might perhaps be expected, because of the mechanical softness of lead, that virtually perfect compacting would be achieved at these high pressures, and that the compression would be the same as that of the massive metal. This proved to be by no means the case, however. After the first application of 25,000 there was no further perceptible change of volume on the second and third applications. In spite of this, the compression, as shown in Table II, was consistently higher, initially by a factor of 1.54 and at 25,000 by a factor of 1.45. The density at atmospheric pressure of the powder after exposure to 25,000 was 10.74, against 11.34 for the massive pure metal. However, only a small part of the difference between these two densities probably represents voids in the compressed powder. The reason for this statement follows. The compression measurements on the powder were continued in the other apparatus to 100,000. After exposure to 100,000 the density was 10.86. The compression of the powder in the range between 25,000 and 100,000 was sensibly the same as that of the massive metal. It is probable therefore that the pressure of 100,000 was enough to sensibly squeeze out all the voids. The difference between the densities 10.86 and 11.34 is probably to be laid to the account of impurities having

considerable mechanical strength, occluded on the surface of the grains of powder, perhaps oxides. In the present experiments only the difference between 10.74 and 10.86 is to be laid to voids. No simple method of effecting a reconciliation between all the figures just given presents itself, but at any rate we have here a dramatic instance of the very great difficulty of getting good values for the compression of compressed powders even under apparently the most favorable conditions.

Graphite. The only measurements of the compressibility of graphite in the literature were made by Richards and collaborators¹¹ on graphite from "both artificial and natural sources."

Measurements were now made on three different grades of material. The first of these was massive graphite prepared at Niagara Falls by the Norton Co., highly purified, and subjected before measurement to a further exposure to approximately 3000° C at atmospheric pressure. This material was very porous, the density at atmospheric pressure after a preliminary excursion to 25,000 being only 1.80. Measurements were made on the massive slug, without the indium sheath. Under 25,000 kg/cm² it experienced a volume change of 11.5 per cent, half of this occurring in the first 5,000 kg/cm². In view of the high porosity it will not pay to give the results in greater detail. The results are chiefly valuable in emphasizing the extraordinary degree to which porosity persists after exposure to high pressures, even in materials comparatively weak.

The second material was Acheson flake graphite, compressed to a slug completely filling the apparatus without the indium sheath. After exposure to 25,000 the density was 2.13; the volume change under 25,000 was 7.5 per cent. The behavior was roughly like that of the Norton massive graphite, with elimination of the very compressible part of the curve in the first few thousand kilograms. The friction and hysteresis of both the massive and the Acheson graphite were not excessive, being about that of the average material of these experiments.

The third material was natural single crystal stock from Ceylon, in the form of flat flakes a few square centimeters in surface area and 0.010 to 0.020 inch thick. Discs of 0.25 inch diameter were cut from the flakes with a tubular cutter, and the discs were piled flat into the pressure chamber, without the indium sheath. The density at atmospheric pressure after precompression to 25,000 was 2.23. Results with this

material were very satisfactory. Friction and hysteresis were minimal, being no greater than for indium itself. Neither was there any region of abnormally high compressibility at the low pressures, but the internal evidence was that the material is sensibly compact. The volume decrement under 25,000 was 5.35 per cent; the results are given in Table II. The initial compressibility, extrapolated to atmospheric pressure, is 2.92×10^{-6} , to be compared with "not greater than 2.9×10^{-6} " by Richards and collaborators.¹¹ The compressibility of graphite appears to be about fifteen times as great as that of diamond, not a surprising result in view of the great difference of densities.

2. Inorganic Salts.

A. *Univalent Nitrates.* Results have been presented in the preceding paper for the compression of these substances in the complete pressure range up to 100,000 kg/cm². The measurements with the present apparatus up to 25,000 were made primarily to provide the necessary fiducial volume decrement needed before the measurements to 100,000 could be reduced, and also to provide the initial part of the compression curve, the compression of these substances not having been previously measured in any extensive pressure range. In general the materials were the same as have been used in previous investigations of polymorphic transitions under pressure;¹² reference is made to the previous paper for details. The results are given in Table III, to one more significant figure than in the preceding work to 100,000. The values given here are those obtained immediately with the present apparatus, with no attempt to reconcile the measurements in the lower range with those to be reported presently in the higher range.

Apparently the only compressibilities in the literature by other observers for any of the nitrates are by Madelung and Fuchs¹³ for NaNO₃ and AgNO₃. For the compressibility of these in the pressure range 200 to 500 kg/cm² they found 3.75 and 3.60×10^{-6} respectively against the values 3.8 and 3.5 given by extrapolation of the values in Table III. There are also measurements of my own¹⁴ on the linear compression in different directions of the single crystal up to 12,000 kg/cm². The cubic compressibility may be calculated from the linear compression. The initial compressibility is 3.85×10^{-6} against the value 3.8 above. The volume decrement at 10,000 kg/cm² obtained by calculation from the

TABLE III
COMPRESSION OF NITRATES

Pressure kg/cm ²	NaNO ₃	KNO ₃	RbNO ₃	CsNO ₃	AgNO ₃	TlNO ₃	NH ₄ NO ₃
2,000	.0074	.0135	.0093	.0103	.0068	.0082	.0117
3,650	{	.0229					
		.1129					
5,000		.1185	.0225	.0247	.0165	.0199	.0274
9,500	{				.0300		
					.0427		
10,000		.0339	.0427	.0460	.0443	.0377	.0499
15,000		.0482	.0608	.0645	.0593	.0534	.0688
20,000		.0611	.0768	.0805	.0725	.0671	.0845
25,000		.0728	.0913	.0943	.0842	.0790	.0979

measurements on the single crystal is 0.0346 against 0.0339 of the present measurements.

It is of interest to consider the relative compressibility of polymorphic forms at a transition. AgNO₃ experiences a transition at 9,500; the data in the table indicate that the low pressure form has a compressibility at the transition point of approximately 2.85×10^{-6} , and the high pressure form at the same point has 3.25×10^{-6} . That is, the compressibility increases on passing through the transition with decrease of volume, a result which appears paradoxical, but which nevertheless is the behavior at the majority of transitions. KNO₃, the only other nitrate with a transition in the present pressure range, shows the opposite behavior. The low pressure form of this is highly compressible, and the compressibility drops rapidly with increasing pressure, from approximately 7.4×10^{-6} at atmospheric pressure to 5.2×10^{-6} at the transition point at 3,600 kg/cm². The compressibility of the high pressure modification at this point is 4.2×10^{-6} , a 20 per cent drop. Above 3,600 the compressibility drops at a slower rate than does that of the low pressure modification.

B. *Certain Halogenates and Perhalogenates.* Previously¹⁴ a study has been made up to 50,000 kg/cm² of the polymorphic transitions of univalent compounds of the types R Hl O₃ and R Hl O₄, where Hl stands for one of the halogens: chlorine, bromine or iodine. Measurements of the compressions of these same compounds are now given here. In general, the materials were the same as used before, left from the previous work, and the previous paper may be consulted for such details as purity. Three of these substances, however, were new: LiClO₄, NaClO₄, and KClO₄. These had been specially purified by Professor K. Fajans, who was interested in their properties from another point of view, and who requested me to measure their compressions. He has discussed the results in another place.¹⁵ The prepa-

ration of these three salts offers unusual difficulties, and Professor Fajans exercised unusual precautions to secure high purity and freedom from moisture. They were supplied to me in glass stoppered paraffine covered bottles. The pressure apparatus was set up as rapidly as possible in order to avoid absorption of moisture from the air. The entire time from opening the bottle to complete enclosing in the pressure apparatus and preliminary application of pressure was about 5 minutes; during most of this time the material was partially covered, exposed to air only on edges and corners.

Of these three perchlorates, LiClO₄ has a transition not known before in the average neighborhood of 16,400 kg/cm². The transition is very sticky; it does not start with increasing pressure until about 19,000, and runs slowly, probably being completed only just below the top pressure. On decreasing pressure the reverse transition does not start until reaching 13,000. The compression of the low pressure form should be satisfactory, but under the conditions the change of volume on passing through the transition and the compression of the high pressure phase can be expected to be only rough.

The results are given in Table IV. In general, the compression increases on passing from lithium to sodium to potassium to rubidium to caesium, although there is an exception in the relative position of rubidium and caesium in the perchlorates. Analogy, and also experience with the simple halogen compounds of the type NaCl, would lead to the expectation that compression should similarly increase on passing from chlorine to bromine to iodine. This effect, however, is much less marked in these compounds. It is recognizable in the series NaClO₃, NaBrO₃, NaIO₃, but in the perchlorates of sodium, potassium, and rubidium there is a falling off of compression on passing from the chlorine compounds to those of iodine which seems beyond any possi-

TABLE IV
 COMPRESSION OF HALOGENATES

Pressure kg/cm ²	NaClO ₃	KClO ₃	CsClO ₃	$\Delta V/V_0$ NaBrO ₃	AgBrO ₃	NaIO ₃	KIO ₃	NH ₄ IO ₃
2,000	.0069	.0104	.0108	.0071	.0057	.0068	.0068	.0057
5,000	.0165	.0259	.0257	.0171	.0138	.0165	.0161	.0138
10,000	.0307	.1044 ^a	.0478	.0320	.0266	.0312	.0298	.0266
15,000	.0431	.1217	.0666	.0450	.0384	.0444	.0417	.0384
20,000	.0542	.1362	.0827	.0567	.0490	.0564	.0522	.0490
25,000	.0644	.1483	.0967	.0673	.0586	.0675	.0619	.0586

^a Transition at 7,500 with volume decrements .0388 and .0944

COMPRESSION OF PERHALOGENATES

Pressure kg/cm ²	LiClO ₄	NaClO ₄	KClO ₄	RbClO ₄	$\Delta V/V_0$ CsClO ₄	NH ₄ ClO ₄	NaIO ₄	KIO ₄	RbIO ₄	NH ₄ IO ₄
2,000	.0078	.0079	.0088	.0102	.0098	.0125	.0078	.0079	.0093	.0081
5,000	.0189	.0191	.0213	.0245	.0232	.0288	.0184	.0190	.0219	.0195
10,000	.0359	.0364	.0404	.0460	.0427	.0519	.0336	.0355	.0400	.0368
15,000	.0509	.0519	.0574	.0647	.0598	.0716	.0463	.0497	.0553	.0524
20,000	.0802 ^a	.0659	.0724	.0817	.0750	.0885	.0569	.0617	.0685	.0664
25,000	.0928	.0784	.0854	.0971	.0890	.1031	.0658	.0820	.0809	.0791

^a Transition at 16,400, with volume decrements .0557 and .0717

ble experimental error. In searching for an explanation, the effect of crystal structure must obviously be taken into account, polymorphism being common, and there being several types of possible structure.

Previous measurements¹⁶ have been made on the linear compression of single crystals of NaClO₃ and NaBrO₃ in the range up to 12,000 kg/cm². The initial compressibilities calculated from these measurements are 4.9 and 4.3 × 10⁻⁶ respectively, against 3.6 and 3.7 given by extrapolation of the values in Table IV. The discrepancy is much beyond the experimental error of the present method, and the explanation of it is not clear. However, it is probable that the previous measurements should be disregarded; these were made by a new method, which has been applied to only a few substances, and which has never been adequately checked. The method was especially devised to apply to substances which are acted on by kerosene, and employed smaller samples than usual, mounted in a complicated way under the surface of mercury.

3. Organic Solids.

A. Definite Compounds. A few simple compounds were investigated, with a range of types of composition. They were taken from the regular stock of the Harvard Chemical Laboratory. In spite of the mechanical softness of organic solids in general under atmospheric conditions, the indium sheath was used in all the measurements. This proved to be necessary, the difference

between the ascending and descending branches in general being of the same order of magnitude as for the inorganic compounds. This is perhaps not too surprising, because it has already been found that under high pressures such organic compounds as rubber may acquire a high rigidity, greater even than that of mild steel under the same pressure.

The results are collected in Table V. Under the name of each substance is the density assumed in the calculations. This density was obtained from the measurement of the dimensions of the charge after release of pressure and removal from the apparatus. It is likely to be slightly and consistently in error on the small side, because of a slight swelling in volume on removal from the apparatus due to the elastic springing back of voids not crushed completely flat by the high pressure. The assumed density enters the calculation in such a way that, if at some future time better values are obtained for the density of the perfectly compacted material, the relative compressions given in the table may be corrected by multiplying by the ratio of the corrected density to the assumed density. This means that in general the volume compressions given in Table V are probably slightly too low.

Among these organic solid compounds the compression at 25,000 kg/cm²; ranges from 0.1959 for menthol to 0.0901 for dextrose, or by a factor of 2.2. The initial compressibilities of these two substances, extrapolated to atmospheric pressure, are in the ratio 3.5. This is consistent with the

TABLE V
COMPRESSION OF ORGANIC SOLIDS

Pressure kg/cm ²	Levulose	Dextrose	Dextrin	Starch	Menthol	Naphthalene	Anthracene	Triphenyl Methane	Thymol	Succinic Acid	Anthro- quinone	Benzo- phenone	Amino-Benzoic Acid		
	1.570	1.467	1.48	1.45	0.923	1.154	1.197	1.106	1.014	1.506	1.398	1.140	ortho-	meta-	para-
2,000	.0100	.0101	.0203	.0234	.0342	.0309	.0240	.0293	.0235	.0178	.0215	.0296	.0168	.0225	.0235
5,000	.0239	.0239	.0452	.0486	.0701	.0630	.0505	.0598	.0694	.0405	.0453	.0605	.0374	.0425	.0493
10,000	.0445	.0439	.0764	.0794	.1114	.1076	.0842	.0961	.1094	.0705	.0743	.0981	.0644	.0665	.0813
15,000	.0625	.0611	.1004	.1023	.1428	.1281	.1095	.1230	.1380	.0940	.0965	.1255	.0863	.0848	.1054
20,000	.0783	.0763	.1194	.1213	.1702	.1493	.1291	.1437	.1612	.1130	.1146	.1473	.1045	.1004	.1252
25,000	.0923	.0901	.1353	.1387	.1959	.1674	.1460	.1618	.1829	.1290	.1307	.1657	.1203	.1146	.1428

general experience that a compressibility, initially high, tends to drop off more rapidly with increasing pressure.

There is a rough correlation between the compressions and the densities, the least dense compounds being in general more compressible; the correlation is better at high than at low pressures. The correlation is still closer if one plots the compressibility at the upper end of the pressure range. This is shown in Figure 4, in which are

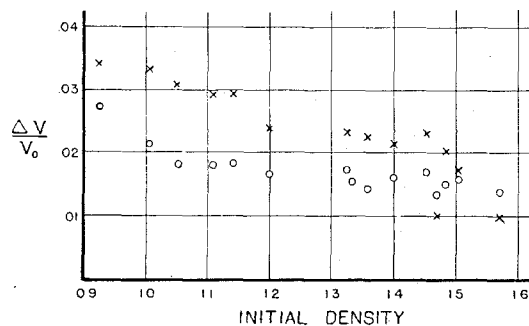


FIGURE 4. The compression of various organic solids as a function of the initial density. The crosses show the relative volume decrements between atmospheric pressure and 2,000 kg/cm², and the circles the relative decrements between 20,000 and 25,000.

plotted as crosses the volume decrement from 0 to 2,000 kg/cm², and as circles the volume decrement between 20,000 and 25,000 kg/cm². The latter set of points lies more nearly on a single curve, and furthermore the curve which best represents the points runs with less change of height from low density to high density. The correlation with density is not materially changed if one plots the final compressibility against the final density instead of against the initial density. In any event, the final compressibility for the denser materials tends to level off to an approximately constant value of 3×10^{-6} . The substances for which there is the greatest failure of correlation between density and compressibility, both at high and at low pressures, are starch and dextrin, the former having abnormally high compressibility and the latter abnormally low.

The reversal of order of densities with pressure in the series of isomeric forms of amino-benzoic acid merits special mention. At atmospheric pressure the densities increase in the order para, ortho, meta, whereas at 25,000 the order is meta, para, ortho, involving a transfer of the meta compound from the head to the foot. The subject is worth further investigation.

It is natural to look for a correlation between the compression at high pressures and the chemical composition. This, however, did not prove especially fruitful. It appears that there is a general tendency for compounds with a large proportion of carbon or of hydrogen in their composition to be relatively compressible, and with a large proportion of oxygen to be relatively incompressible, but further than this no obvious correlation appeared.

B. Synthetic and Natural Rubbers. The measurement of these was undertaken at first for the entirely practical purpose of finding some way of predicting which might be expected to function best for high pressure packing on the piston of the apparatus for 30,000 kg/cm². There is considerable difference in the behavior of different rubbers as packings; most rubbers crack at these high pressures, and in some the cracking is so extensive that leak is of frequent occurrence. The cracking probably arises from a combination of circumstances. In the first place, the rubber becomes harder and brittle under pressure exactly as when plunged into liquid air, the phenomenon being essentially a raising of the freezing point with pressure. In the second place, the rubber thus embrittled must be deformed by the unilateral compressive stress arising from the unsupported area principle of the packing sufficiently to neutralize the effect of the uniform volume compression which it would receive under the action of the fluid pressure alone, so that it will again tightly fill the packing space; otherwise leak will occur. This deformation of the embrittled rubber is the probable origin of the cracking. One would expect that, other things being equal, it would be least in those rubbers with the smallest natural volume compressions, and this was the clue followed in the exploration. The distortion necessary to bring the rubber back to fill the packing hole is not small at these pressures. Thus one typical synthetic shows a volume loss of 21 per cent at 25,000 kg/cm²; the corresponding decrease of linear dimensions is 7.6 per cent, which means that the embrittled solid must expand under the unilateral compressive stress by some 8.2 per cent in linear dimensions, preferably without cracking. No rubber has been found entirely free from cracking under these conditions; the best that can be hoped is to find one in which the cracks that do form are not so serious but that they can be sufficiently sealed by the lateral compression.

Ten different specimens of various synthetic

rubbers were collected from dealers in the neighborhood of Boston. Measurement disclosed an interesting feature, namely in some of them there was a rather sharp change in the direction of the curve of volume versus pressure, or discontinuity of the second kind, at pressures roughly of the order of 5,000 kg/cm². I had the privilege of discussing this result with Dr. E. Guth, and it seemed to him of sufficient interest to justify examination of specimens whose composition was more definitely known than of the commercial specimens. He accordingly was kind enough to send me 6 representative rubbers of which the compositions are known; the results for four of these are included here and those for the other two will be published later.

The compositions are as follows:

	Hevea Gum	Hevea Tread
SS	100	100
Stand. Micronex	—	52
ZNO (Fast Curing)	3	3
Stearic Acid	4	4
Pine Tar	2	2
Antioxidant	1.5	1.5
S	2.7	2.7
Captax	0.9	0.9

	Butyl Gum	Butyl Tread
Butyl B	100	100
Zinc Oxide	5	5
Stearic Acid	3	3
Sulfur	1.5	1.5
Cabot no. 9, Black	—	50
Treads	1	1
Captax	—	0.5

The retraction process and certain other physical properties of the Hevea rubber have been described in recent letters in the *Physical Review*.¹⁷ Certain properties of the butyl rubber are to be published in a forthcoming number of the *Journal of Applied Physics*, and were presented at the Rochester meeting of the American Physical Society in the summer of 1944.

The material was cut to the full diameter of the carboloy container and used without the indium sheath. The specimens from Dr. Guth were dimensioned with particular care, being ground to dimensions on one flat face and on the curved face.

In Table VI the compressions for 12 synthetic rubbers and 2 natural rubbers are given. The table also gives the densities at atmospheric pressure calculated from the measured dimensions of the charge at atmospheric pressure, be-

TABLE VI
COMPRESSION OF SYNTHETIC AND NATURAL RUBBERS

Pressure kg/cm ²	$\Delta V/V_0$													
	Duprene no. 89023	Koroheel no. 832	Neoprene no. 832	Buna S no. 8774	Ameripol D-7700	Hood 844A	Goodrich D-402	Goodrich D-420	Goodrich D-453	Goodrich D-453	Butyl Gum	Butyl Tread	Hevea Gum	Hevea Tread
2,000	1.589	1.250	1.357	1.376	1.370	1.176	1.193	1.350	1.513	1.309	0.967	1.125	0.950	1.122
5,000	.0302	.0511	.0460	.0465	.0367	.0407	.0422	.0385	.0329	.0432	.0519	.0423	.0535	.0462
10,000	.0615	.0967	.0956	.0872	.0715	.0792	.0837	.0745	.0636	.0842	.0945	.0807	.1017	.0870
15,000	.0898	.1403	.1294	.1238	.1052	.1163	.1194	.1128	.0938	.1208	.1303	.1129	.1422	.1250
20,000	.1198	.1679	.1567	.1493	.1304	.1445	.1454	.1378	.1162	.1480	.1543	.1334	.1697	.1490
25,000	.1301	.1891	.1793	.1715	.1507	.1663	.1670	.1587	.1347	.1692	.1744	.1510	.1929	.1707
	.1462	.2060	.1990	.1903	.1686	.1840	.1847	.1769	.1513	.1862	.1920	.1667	.2116	.1900
Pressure of	3,500	4,800	4,800	6,300	4,900		4,800				6,200			6,500
Discontinuity Amount														
of	2.0×10^{-6}	5.3×10^{-6}	3.4×10^{-6}	1.5×10^{-6}	1.5×10^{-6}		3×10^{-6}				5×10^{-6}			2×10^{-6}
Discontinuity $\Delta V/V_0$														
at														
Discontinuity Ratio of	.0516	.0939	.1012	.0707	.0851						.1083			.1026
Width of														
Hysteresis														
Loop to														
Maximum Displacement	.083	.059	.082	.087	.064	.067	.072	.080	.103	.077	.083	.090	.074	.073

for it had been removed from the pressure apparatus. Thus the expansion on removing from the apparatus, which was a source of error in some of the other densities, was not present in these measurements for rubber, which should be substantially correct. It will be seen that, just as in the case of the solid organic compounds, there is a certain correlation between the compression and the density. This correlation is, however, not so close for the rubbers as for the compounds, as indeed might be expected in view of the fact that there is an artificial factor in the density of the rubbers in the varying degree of loading with carbon black.

The table gives data for the discontinuity of the second kind, that is, the discontinuity in slope, exhibited by 7 of the rubbers. There is listed the pressure of the discontinuity, the volume decrement at the pressure of discontinuity, and the amount of discontinuity in the

derivative $\left(\frac{\partial v}{\partial p}\right)_\tau$; in all cases the discontinuity is

in the direction of a smaller slope at the higher pressure. No great amount of precision can be claimed for the numerical values of these discontinuities, as is always the case in attempting to measure a discontinuity. In fact, from the point of view of logical rigor, not even the existence of a discontinuity in the mathematical sense can ever be established by physical measurements; it is merely that a discontinuity is the simplest way of reproducing the results to the natural order of accuracy. In any event, there can be no mistaking the striking qualitative difference between the curves for substances like neoprene and Hevea gum. An active imagination would be tempted to find other discontinuities in the curves than those given; only the apparently inescapable ones were listed. One particularly tempting example is afforded by Hood 844A, in which there seems to be rather

definitely a discontinuity in $\left(\frac{\partial^2 v}{\partial p^2}\right)_\tau$ near 6,000

kg/cm². The physical significance of these discontinuities is probably merely that some rubbers

pass more abruptly into the "frozen" condition than do others.

Table VI contains, in addition to the matters just discussed, the width of the hysteresis loop, that is, the ratio of the maximum difference between displacements with increasing and decreasing pressure to the maximum displacement. This varies by a factor of 1.75 fold, somewhat more than does the density or the compressibility. Several factors obviously enter into the width of the loop. There is in the first place the ordinary coefficient of friction of the rubber against the carboly walls. In the second place there is the internal plastic flow stress within the body of the rubber. In the third place, there is lag, sub-cooling or superheating, between the ordinary state and the "frozen" state.

Returning to the problem which originally suggested the measurement of the rubbers, it is to be remarked that the single criterion of compression at high pressures did not prove an adequate characterization of the behavior as a high pressure packing. There are other features which are involved in the functioning as packing. Thus, the friction with the steel walls of the pressure vessel must not be too great, and the shearing strength against this frictional drag must be sufficient. Certain of the artificial rubbers which appeared promising from the point of view of volume compression had such a combination of high coefficient of friction and low mechanical strength that when used as packing a vortex ring of rubber was detached from the body of the packing at the periphery and rolled over and over against the steel walls as the plunger advanced. It still remains necessary to make actual trial to determine the suitability for high pressure packing. As yet, exhaustive trial has not been made of the suitability of all the rubbers for high pressure packing, but to date Duprene seems the best for all round use. It happens that Duprene also has the smallest compression.

I am indebted to my mechanic Mr. Charles E. Chase for the skillful construction of the apparatus, and to the Carboly Company for the carboly used in this and the preceding paper.

RESEARCH LABORATORY OF PHYSICS,
Harvard University, Cambridge, Mass.

REFERENCES

- ¹ P. W. Bridgman, Proc. Amer. Acad. 74, 21-51, 1940.
- ² P. W. Bridgman, Proc. Amer. Acad. 71, 387-460, 1937.
- ³ T. W. Richards and J. D. White, Jour. Amer. Chem. Soc. 50, 3290-3303, 1928.
- ⁴ P. W. Bridgman, Proc. Amer. Acad. 74, 425-440, 1942.
- ⁵ P. W. Bridgman, Proc. Amer. Acad. 68, 39, 1933.
- ⁶ T. W. Richards, Jour. Amer. Chem. Soc. 37, 1646, 1915.
- ⁷ P. W. Bridgman, Proc. Amer. Acad. 60, 346, 1925.
- ⁸ Ref. 4, p. 434.
- ⁹ P. W. Bridgman, Proc. Amer. Acad. 72, 207-225, 1938.
- ¹⁰ P. W. Bridgman, Proc. Amer. Acad. 74, 11-20, 1940.
- ¹¹ T. W. Richards, W. N. Stull, F. N. Brink, and F. Bonnet, Jr., Carn. Inst. Wash. Pub. No. 76, p. 39, 1907.
- ¹² P. W. Bridgman, Proc. Amer. Acad. 72, 45-135, 1937.
- ¹³ E. Madelung und R. Fuchs, Ann. d. Phys. 65, 289-309, 1921.
- ¹⁴ P. W. Bridgman, Proc. Amer. Acad. 64, 66, 1929.
- ¹⁵ K. Fajans, Phys. Rev. 61, 543, 1942. There are also two doctoral dissertations, giving other results on LiClO_4 , prepared under the supervision of Professor Fajans, by Oliver Johnson (December 1942) and Jean Chien-Han Chu (December 1943), at present available only in typewritten form.
- ¹⁶ Ref. 14, p. 64.
- ¹⁷ B. A. Mrowca, S. L. Dart and E. Guth, Phys. Rev. 66, 30, 1944; B. A. Mrowca, S. J. Dart and E. Guth, Phys. Rev. 66, 32, 1944; H. M. James and E. Guth, Phys. Rev. 66, 33, 1944.

Proceedings of the American Academy of Arts and Sciences

VOL. 76, No. 2, P. 25-54—APRIL, 1947

**LOWER PERMIAN INSECTS FROM OKLAHOMA. PART 1.
INTRODUCTION AND THE ORDERS MEGASECOPTERA,
PROTODONATA, AND ODONATA**

BY FRANK M. CARPENTER

LOWER PERMIAN INSECTS FROM OKLAHOMA. PART 1.

INTRODUCTION AND THE ORDERS MEGASECOPTERA, PROTODONATA, AND ODONATA

BY FRANK M. CARPENTER

Received August 9, 1946

Presented October 9, 1946

INTRODUCTION

During the past two decades our knowledge of Permian insects has been greatly increased. This has mainly resulted from the collection and study of several thousand specimens from strata in Kansas, Russia and Australia. The rocks in Kansas, termed the Elmo limestone by Dunbar (1924), are geologically the oldest; they belong to the Wellington formation, which is well within the Lower Permian and not far from its base. The correlation of the Russian and Australian beds is not so certain, but they are probably correctly referred to the Upper Permian. The Elmo beds have accordingly been unique: they have provided us with almost the sole record of an early Permian insect fauna. It has been my hope for many years that another insect-bearing bed of equivalent age would be found, especially one deposited under environmental conditions different from those responsible for the Elmo limestone.

This hope has now been realized. In 1939 Dr. G. O. Raasch sent me about seventy well-preserved insects which he had collected in certain Wellington strata in Noble County, Oklahoma. A study of the specimens convinced me that further exploration of these rocks would add substantially to our knowledge of Permian insects, and I accordingly spent the following summer collecting in the region. In this undertaking I was fortunate in having the aid of Dr. Raasch, who made a careful stratigraphic study of the area, and was able to trace the insect-bearing rocks over an area of about 400 square miles. In about ten weeks we collected more than five thousand well-preserved insects.

Dr. Raasch's detailed account of the Wellington formation in Oklahoma is being published elsewhere, but with his permission I include here a summary of his conclusions on the origin of the insect-bearing rocks and the environment of the biota. The Wellington formation as a whole covers a large area. It was deposited in a great water-filled basin, the Wellington Sea, occupying parts of Oklahoma, Kansas, Nebraska and Colorado. In Pennsylvanian time typically marine waters from the ocean to the

south periodically invaded the basin and this inflow continued until early Wellington time. By mid-Wellington, typically marine conditions had ceased to exist in the basin and the climate of the region had become more arid. Although inflow of marine waters continued periodically, presumably through a restricted connection from the open sea to the southwest, the waters covering the basin were at all times of more than marine salinity. The conditions alternated between those of a great salt lake and of a vast, desiccating mud-pan. This alternation was especially pronounced at the time of deposition of the strata in Noble County which Raasch has termed the Midco member of the Wellington formation. This member is about 255 feet thick and is composed mainly of alternating lumpy, clay-shales and fissile, flaky shales. Included in this series is the insect bed. Varying from about six inches to four and a half feet in thickness, it consists in reality of several layers of fine-grained, compact, argillaceous dolomitic limestone, separated by fissile shale. Three of the limestone layers contain insects, and for convenience of reference they have been designated the *lower*, *middle* and *upper* insect layers. The lower layer shows sedimentational and organic features which suggest that it was laid down close to the shore and that most of its biota was washed into the lake. The matrix and biota of the middle layer, which is highly irregular and characterized by pink partings, were probably transported to the water by violent dust storms. The upper layer is highly argillaceous, and was deposited under strongly saline conditions; insects are rare but they are very well preserved.

Midco Salt Lake was essentially a playa, barren of life except for algae and Conchostraca (Crustacea). There is no evidence that insects, either nymphs or adults, lived in the water of the lake itself. Most insects preserved in the limestone were presumably carried to the water by gales or floods and were therefore not all derived from the local environment. Thus, the aquatic nymphs which are abundant at a few localities (e. g. loc. 15) were almost certainly brought to the lake intermittently by small streams

in a flooded condition. Plants did not grow near the lake; they are sparsely represented in the beds by fragments of leaves or wood, which were also carried to the water by winds and floods.

The foregoing account describes a very different environment from that existing in the vicinity of Insect Hill in Kansas, when the Elmo limestone was formed. According to Dunbar (1924) this bed was deposited in a fresh-water lake or lagoon, derived from an earlier swamp. Plants apparently grew close to the water's edge and although most insects were driven into the water by occasional storms, some lived in the water during their nymphal stages. The Elmo Lake was much smaller than the Midco and consequently presented less diverse environmental conditions. Nevertheless, the two lakes were only about 140 miles apart and apparently nearly contemporaneous.

The Xiphosura and Conchostraca which Dr. Raasch and I collected in the Midco beds have already been studied and described by Professor P. E. Raymond (1945, 1946). Three specimens of Xiphosura, found in the lower layer at locality 15, represent two new species of a new genus: *Anacantium carpenteri* Raym. and *A. breve* Raym. The genus belongs to the family Euproöpidae, previously known only from Carboniferous strata. The Conchostraca include seven species, all new and representing three families: Lioestheriidae, with *Lioestheria raaschi* Raym., *Pseudestheria brevis* Raym., *Ps. plicifera* Raym., and *Ps. rugosa* Raym.; Limnadiidae, with *Pemphicyclus laminatus* Raym. and *Palaeolimnadiopsis carpenteri* Raym.; and Leaiadidae, with *Leaia reflexa* Raym. The occurrence of the Leadidae is especially interesting, since the family has previously been known only from Carboniferous strata. *Pseudestheria plicifera* is also noteworthy, for it is the species which occurs, though very rarely, in the Elmo limestone. Apart from the occurrence of insects, the extraordinary abundance of Conchostraca is the most striking characteristic of the Midco fauna. Although these Crustacea were probably unable to develop prolifically in the hypersaline water of the Lake, they presumably became well established after cyclical inflow of fresh water, which undoubtedly occurred in the spring of certain years. Subsequent evaporation of much of the water in the Lake would cause a reversion to hypersalinity and result in the death of masses of adult Conchostraca. Their eggs, however, presumably survived through this period and hatched when the water again became habitable.*

* This is suggested by Sars' experiments (1896) on

Very little can be said at this time about the Midco insect fauna. It obviously includes the same orders as that at Elmo, as well as many of the genera and a few species; but it also contains families which are not known from the Elmo limestone and even several which have previously been found only in Carboniferous rocks. This is particularly interesting in view of the Carboniferous affinities of some Midco Xiphosura and Conchostraca. A satisfactory comparison of the insects of the two beds cannot be made until studies of both faunas have been completed.

Because of the extent of the Midco insect beds, our collections were made at widely scattered localities in the area. Furthermore, since these localities undoubtedly represent some diversity of environments, record has been kept, by number, of the locality at which each fossil was collected. The approximate site of the localities is given in the accompanying table. Similar record has been kept of the layers of the insect bed in which the specimens were found, the letters L, M, U, indicating the lower, middle and upper layers respectively. The present collection of Midco insects is presumably by no means representative of the fauna. My original project of making a series of annual trips to the beds, although temporarily halted by the war, will now be carried out until a more extensive collection has been secured.

Before closing these introductory remarks, I wish to acknowledge the aid of the Geological Society of America, which financed in part the 1940 collecting trip with a grant from the Penrose Bequest (Project Grant 335-40). All who are interested in fossil insects are deeply indebted to Dr. Raasch for his discovery of one of the most important insect-bearing beds known; and I, in particular, am indebted to him for his indispensable help as a technical field assistant. I am also obligated to Mr. F. H. Ward, of Ward's Natural Science Establishment, for his part in introducing me to Dr. Raasch's discovery. Finally, both Dr. Raasch and I owe thanks to our friends in Noble County who allowed us to collect without restraint on their property.

The following pages deal with the Midco insects belonging to the Orders Megasecoptera, Protodonata and Odonata. Other orders will be treated in subsequent papers in this series.

the eggs of Limnadia, which developed normally after resting at least seven years in dried mud. From other observations he concluded that these eggs, in order to be able to develop at all, need to lie dry for several successive years.

- Loc. 1. Sw. corner, Sec. 28, T23N, R1W.
 Loc. 2. Sw. $\frac{1}{4}$ of Sw. $\frac{1}{4}$, Sec. 20, T23N, R1W.
 Loc. 3. Nw. $\frac{1}{4}$ of Nw. $\frac{1}{4}$, Sec. 4, T23N, R1W.
 Loc. 4. Se. $\frac{1}{4}$ of Ne. $\frac{1}{4}$, Sec. 34, T22N, R1W.
 Loc. 5. Sw. $\frac{1}{4}$ of Se. $\frac{1}{4}$, Sec. 4, & Nw. $\frac{1}{4}$ of Ne. $\frac{1}{4}$, Sec. 9, T23N, R1W.
 Loc. 6. Sw. $\frac{1}{4}$ of Sw. $\frac{1}{4}$, Sec. 10, T23N, R2W.
 Loc. 7. Ne. $\frac{1}{4}$ of Nw. $\frac{1}{4}$, Sec. 34, T22N, R1W.
 Loc. 8. Nw. $\frac{1}{4}$ of Nw. $\frac{1}{4}$, Sec. 34, T22N, R1W.
 Loc. 9. Roadcut $\frac{1}{2}$ mile south of Ne. Corner, Sec. 33, T21N, R1W.
 Loc. 10. Ne. $\frac{1}{4}$ of Nw. $\frac{1}{4}$, Sec. 28, T22N, R1W.
 Loc. 11. Se. $\frac{1}{4}$ of Sw. $\frac{1}{4}$, Sec. 22, T22N, R1W.
 Loc. 12. Ne. $\frac{1}{4}$ of Se. $\frac{1}{4}$, Sec. 34, T22N, R1W.
 Loc. 13. Ne. $\frac{1}{4}$ of Sw. $\frac{1}{4}$, Sec. 13, T23N, R2W.
 Loc. 14. Sw. $\frac{1}{4}$ of Ne. $\frac{1}{4}$, Sec. 14, T23N, R2W.
 Loc. 15. Sw. $\frac{1}{4}$ of Nw. $\frac{1}{4}$, Sec. 2, T21N, R1W.
 Loc. 16. Ne. $\frac{1}{4}$ of Ne. $\frac{1}{4}$, Sec. 33, T22N, R1W.

Table 1. Midco Insect Bed.

1940 Localities by sections, ranges, and townships, in Noble Co., Oklahoma.

Order MEGASECOPTERA

This order is represented in the Midco collection by eighteen species, which I have assigned to eight genera and five families. The Elmo beds in Kansas, which are also of Wellington age, have so far yielded eleven species referable to five genera and four families. These figures indicate that the order Megasecoptera is more abundantly and diversely represented in the Midco fauna than in the Elmo fauna. They are especially significant since about twice as many specimens of insects have been collected at Elmo as in the Midco beds.

The families present in the Midco member include all those found in the Elmo fauna and in addition the family Bardohymenidae. The occurrence of the latter is of much interest, since it contains species closely related to *Aspidothorax*, from the European Carboniferous. All the Megasecopterous genera known from Elmo are likewise included in the Midco fauna, with the single exception of *Permohymen*. Three new genera are represented in the Midco beds, as well as one genus (*Sylbohymen*) described from the Russian Permian, but not known from Elmo. Four of the eighteen species from Oklahoma are apparently identical with those from Elmo; the others are new.

Some of the new species, especially the Martynoviids, furnish interesting evidence bearing on the interpretation of the wing venation of the Megasecoptera and its phylogenetic importance. It is now apparent that the order was a much larger and diversified group than has previously been supposed, with at least two distinct phylogenetic lines within the order. The evidence for these statements and other conclusions which I have reached will be discussed below, after the description of the fossils.

Family ELMOIDAE

This interesting family has previously been known only from one species, *Elmoa trisecta* Till., from the Kansas Permian. In the Oklahoma collection there

are six specimens representing two new genera and four new species, in addition to *trisecta*. This material provides us with additional information about the family and requires slight modification of the characteristics previously suggested for the group (Carpenter, 1943). In the new specimens, some of which are splendidly preserved, the stem of R is obviously free from the stem of CuA. This condition undoubtedly existed in *Elmoa*, but the flattening of the convexities and concavities at the base of the wing in the specimens of *Elmoa* presumably caused the apparent fusion of the two stems. All well-preserved specimens of Elmoidae have the stem of R very strongly convex, that of CuP strongly concave. The stem of CuA, which joins CuP only at the very base of the wing, is situated on the steeply inclined membrane between R and CuP. Also in all the new species there are at least three anal veins, instead of two, as in *Elmoa*. This is an especially important characteristic, not elsewhere known among the Megasecoptera.

The outstanding characteristics of the Elmoidae are (1) the independence of the stems of R and CuA, (2) the absence of coalescence between Rs and MA, and (3) the proximal convergence of the strongly convex CuA and R, forming an angle bisected by stem of M. The last characteristic is present also in the Martynoviidae and Asthenohymenidae.

The family Elmoidae, especially as represented by the new genus *Parelmoa*, appears to have a relatively generalized venation and to have several venational features suggestive of the Palaeodictyoptera. Indeed, arguments for placing *Parelmoa* in the Palaeodictyoptera could readily be advanced; but any such assignment would involve not only *Elmoa*, but the Martynoviidae and Asthenohymenidae. Also concerned in this question is the Carboniferous genus *Diaphanoptera*, a detailed account of which is being published elsewhere.¹

¹ Studies on Carboniferous Insects from Commentry, France. Part II (in preparation).

Elmoa trisecta Till.

Elmoa trisecta Tillyard, 1937, Amer. Journ. Sci., **33**: 84. Carpenter, 1943, Proc. Amer. Acad., **75**: 56.

There is a single specimen (4736ab) of this in the material from the Midco beds; it was collected at locality 8-M, and consists of the proximal third of a wing. Its venation, as far as known, is identical with that of the Kansan specimens.

***Parelmoa*, new genus**

Related to *Elmoa*. Fore wing: Sc terminating on costal margin slightly beyond mid-wing, i. e., just beyond first fork of Rs; Rs arising nearer the base than in *Elmoa*, with three branches, and joined by a cross-vein to MA basally (as in *Elmoa*), but the cross-vein is nearer the origin of MA and further from the origin of Rs than it is in *Elmoa*; MA simple, MP forked; CuA and CuP unbranched; 1A well developed, extending to midwing and with three branches; 2A and 3A present, the latter branched from the base. Cross-veins numerous. Hind wing: Sc closer to R than in the fore wing; anal veins apparently as in fore wing.

Genotype: *Parelmoa revelata*, n. sp.

This genus differs from *Elmoa* chiefly in having a longer Sc and greater development of anal veins.

an individual trait). Cross-veins are numerous but weak, except those at base of costal space. The distribution of preserved cross-veins in the type indicates that others discernible in the specimen were originally present. Hind wing unknown.

Holotype: No. 4822ab, Museum of Comparative Zoology, collected in the Midco insect bed (loc. 15-L), Noble Co., Oklahoma, by F. M. Carpenter and G. O. Raasch. The specimen is a complete and splendidly preserved fore wing.

***Parelmoa radialis*, n. sp.**

Figure 2

Fore wing: length, 15 mm.; width, 5 mm. Shape and venation (as far as known) as in *revelata*, except that R4 + 5 is unbranched, and R2 + 3 divides shortly after its origin. There is a suggestion of a terminal twig on R2, but this is almost certainly an individual trait. Only a few cross-veins are present in the type, outside of the costal space. The anal veins are unknown. Hind wing: length, 12 mm.; width, 4 mm.; costal margin and stem of R straighter basally than in fore wing (as is true of *Elmoa*); venation otherwise like fore wing, including the branching of Rs. 1A and 2A unbranched; 3A

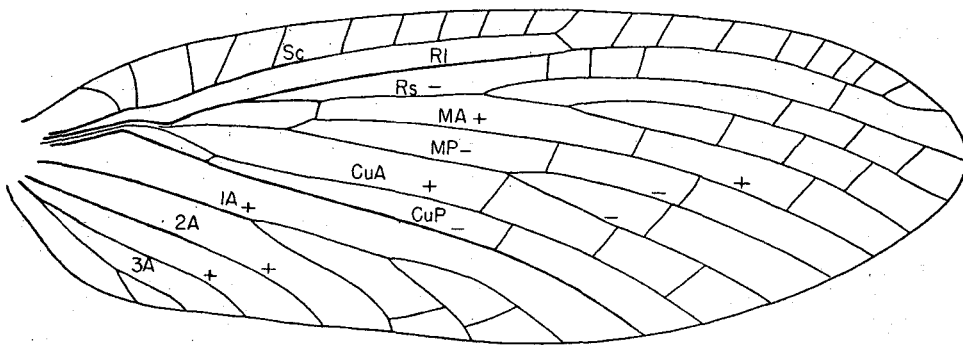


FIGURE 1. *Parelmoa revelata*, n. sp. Drawing of fore wing (holotype). Sc, subcosta (concave); R1, radius (convex); Rs, radial sector (concave); MA, anterior media (convex); MP, posterior media (concave); CuA, anterior cubitus (convex); CuP, posterior cubitus (concave); 1A, 2A, 3A, anal veins.

***Parelmoa revelata*, n. sp.**

Figure 1; plate 2, figure 2

Fore wing: length, 15 mm.; width, 5 mm.; broadest across the middle or not much beyond; Sc connected to R1 by a distal cross-vein; R2 + 3 long, unbranched; R4 + 5 forking slightly after its origin; MP forked at about the level of first fork of Rs; 1A forked at about half its length and again somewhat beyond this; 2A simple; 3A giving rise distally to a posterior branch, which is in turn twigged distally (probably

branched much as in *revelata*. Cross-veins weakly preserved in the type and those of the costal space are not discernible.

Holotype: No. 4825, Museum of Comparative Zoology, collected in the Midco insect bed (loc. 15-L), Noble Co., Oklahoma, by F. M. Carpenter and G. O. Raasch. This consists of a nearly complete hind wing, moderately well preserved. Paratype: No. 4824, (loc. 8-M), Museum of Comparative Zoology, consisting of a well preserved fore wing, lacking the anal area.

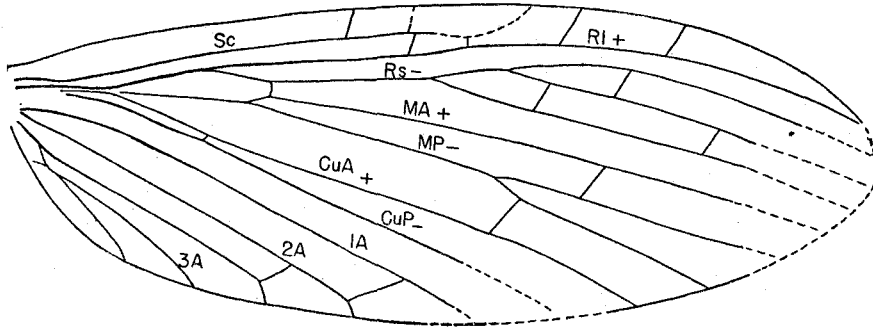


FIGURE 2. *Parelmoa radialis*, n. sp. Drawing of hind wing (holotype). Lettering as in figure 1.

This species is distinguished from *revelata* on the basis of the structure of Rs and 1A. Although the anal veins are lacking in the paratype (fore wing), I have associated this with the holotype (hind wing) because of the similar form of Rs. The difference in branching of Rs in the two species might, of course, be due to individual variation. However, in the seven known specimens of the *Elmoa trisecta* from the Elmoa beds, the branching of Rs is strikingly constant and I assume the same stability for *radialis* and *revelata*. The branching of 1A is also markedly different in *radialis* from what it is in *revelata*, but of course this vein is known only in the hind wing.

***Parelmoa obtusa*, n. sp.**

Figure 3

Fore wing: length, 17 mm.; width, 5.5 mm.; broadest in distal third of the wing; apex broadly rounded; costal margin not so convex as in *revelata* and *radialis*; Sc somewhat longer than in the latter two species; R2 + 3 forked, R4 + 5 unbranched; 1A with a terminal fork; 2A unbranched; 3A with a forked posterior branch. Cross-veins apparently fewer than in *revelata*, many arranged obliquely. Hind wing unknown.

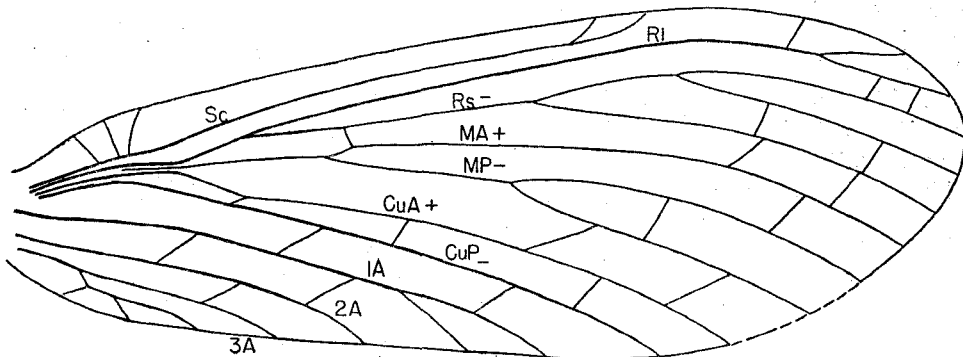


FIGURE 3. *Parelmoa obtusa*, n. sp. Drawing of fore wing (holotype). Lettering as in figure 1..

Holotype: No. 4823 ab, Museum of Comparative Zoology; collected in Mideo insect bed (loc. 15-L), Noble Co., Oklahoma, by F. M. Carpenter and G. O. Raasch. This is a complete and well preserved fore wing.

***Pseudelmoa*, new genus**

Related to *Parelmoa*. Fore wing: Sc extending far beyond level of first branch of Rs; Rs with at least five terminal branches; Rs arising further proximad than in *Parelmoa*; MP forked; three anal veins, 1A long, extending to about mid-wing; cross-veins about as numerous as in *Parelmoa*. Hind wing unknown.

Genotype: *Pseudelmoa ampla*, n. sp.

This genus is notable for the length of Sc and the numerous branches of Rs.

***Pseudelmoa ampla*, n. sp.**

Figure 4

Fore wing: length (as preserved), 20 mm.; width, 6 mm.; estimated length, 22 mm.; costal margin not convex; Sc terminating beyond fork of R2 + 3; MA apparently arising near mid-wing but a weak and probably adventitious vein at this point makes the origin uncertain; 1A with a distal fork; cross-

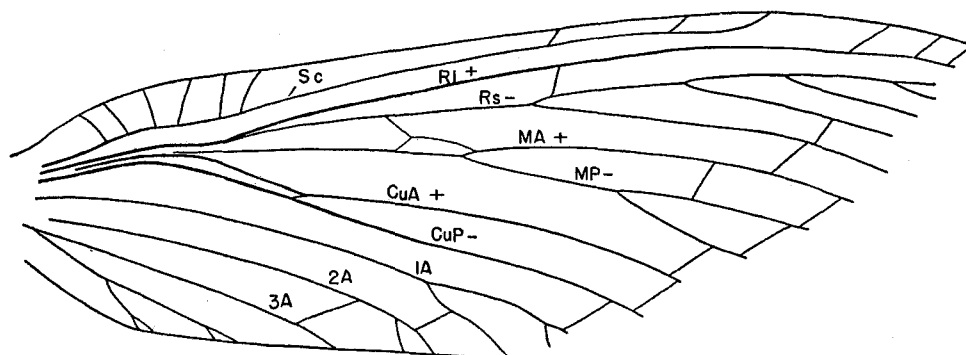


FIGURE 4. *Pseudelmoa ampla*, n. sp. Drawing of fore wing (holotype). Lettering as in figure 1.

veins as shown in figure though probably not all are discernible. Hind wing unknown.

Holotype: No. 2826ab, Museum of Comparative Zoology, collected in the Mideo insect bed (loc. 15-L), Noble Co., Oklahoma, by F. M. Carpenter and G. O. Raasch. This consists of a well preserved fore wing, lacking the distal portion.

Family BARDOHYMENIDAE

This family was erected by Zalesky (1937) for *Bardohymen magnipennifer* from the Permian of Russia. Since the unique specimen representing that species consisted of the distal half of the wing only, the family could not be satisfactorily defined. The collection from Oklahoma contains a complete wing of a species (*Calohymen permianus*, n. sp.) obviously closely related to *Bardohymen*. The family is therefore redefined here with the aid of the information now at hand. We do not, of course, know for certain that the proximal half of the wing of *magnipennifer* is like that of the new species; should it turn out to be very different, a new family will be needed for *Calohymen*. In the Mideo collection there is also an incomplete wing of a species apparently belonging to the genus *Sylvohymen*, which was described by Martynov from the Russian Permian and tentatively referred to the family Bardohymenidae.

The Bardohymenidae were larger than the Protohymenidae. Their venation was much like that of the Carboniferous Aspidothoracidae. The costal space was narrow, R1 being submarginal, at least in the distal half of the wing. Sc is not clear distally; it apparently extended well beyond the origin of Rs, which arose not far from mid-wing and gave rise to at least three branches; M arose at the base of the wing and though close to R, apparently retained its independence from R (as in the Aspidothoracidae) and diverged away from R well before the origin of Rs; MA was not anastomosed with Rs; Cu was ap-

parently anastomosed with the stem of M for a short interval; CuA was not anastomosed with M or MP; a single anal vein was present, formed as in *Aspidothorax*; cross-veins were numerous but there were not more than twenty-five in all. The differences between the fore and hind wings have not been determined; probably the wings were nearly homonomous, as in *Aspidothorax* and most other Megaseoptera.

The closest relatives of this interesting family are the Aspidothoracidae from the Carboniferous of Commeny. Zalesky placed Bardohymenidae in the Suborder Protohymenoptera, presumably because of the proximity of Sc and R1 to the margin; but the family has much more in common with the Aspidothoracidae than with Protohymenidae or its relatives. This is one of the several examples, noted in this paper, of the occurrence of Carboniferous types in the Mideo fauna.

Calohymen, new genus

Related to *Bardohymen*. Sc apparently terminating beyond mid-wing; R1 not forked distally; Rs with three branches; MA, MP, CuA and CuP unbranched; two distinct rows of cross-veins, even the outer row being remote from the posterior margin of the wing.

Genotype: *Calohymen permianus*, n. sp.

Calohymen permianus, n. sp.

Figure 5

Wing: length, 25 mm.; width, 6.5 mm. Costal margin straight for the proximal two-thirds of the wing, then broadly curved; apex slightly rounded; posterior margin only slightly curved; wing broadest at the level of the origin of R4 + 5; R1 diverging slightly away from the margin above the branches of Rs, connected to the margin by two cross-veins (at least in type); no pterostigmal thickening visible;

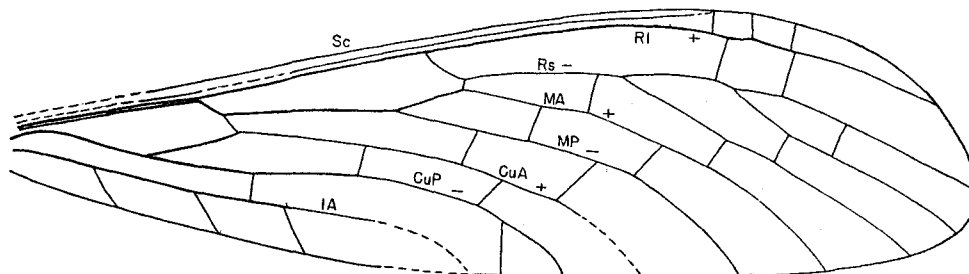


FIGURE 5. *Calohymen permianus*, n. sp. Drawing of holotype. Lettering as in figure 1.

Rs arising slightly before mid-wing; R4 + 5 only a little longer than R3; two long cross-veins between Rs and R1; MA arising slightly proximad of the origin of Rs, connected to Rs by a short cross-vein; CuA arising well before the divergence of M from R1 and connected to M by an oblique cross-vein; CuP has a slight terminal branch, which is probably formed by an oblique cross-vein (as in *Aspidothorax*); 1A with four veinlets leading to the hind margin; between all main veins (except CuP and 1A) there are two cross-veins arranged as shown in figure 5.

Holotype: 4687ab, Museum of Comparative Zoology; collected in Midco insect beds (loc. 15-L), Noble Co., Oklahoma (F. M. Carpenter and G. O. Raasch). It consists of a well preserved wing, complete except for a small piece along the posterior margin at the end of CuA.

This species is of much interest because of its resemblance to *Aspidothorax*, a drawing of which is included here (figure 6).² Unlike the condition in *Protohymenidae*, etc., MA is free from Rs and CuA is free from M. So close is *Calohymen* (and presumably *Bardohymen*) to *Aspidothorax* that it is difficult to find many differences between the two. Sc is possibly slightly longer in *Aspidothorax* than in *Calohymen*; MP is deeply forked in *Aspidothorax* but

² An account of the structure and relationships of *Aspidothorax* is included in my revisional study of *Commentry* insects, Part II, now in preparation.

simple in *Calohymen*; and the number of cross-veins in *Aspidothorax* is approximately twice that in *Calohymen*. These differences are probably sufficient to justify the retention of the family *Bardohymenidae*, but they are much less than have previously been found between Permian and Carboniferous Megasecoptera.

Genus *Sylvohymen* Martynov

Sylvohymen Martynov, 1940, Trav. Inst. Paleont.

11: 10.

This genus was based on a distal fragment of a wing (*robustus*) and placed by Martynov in the family *Bardohymenidae*, although its relationships will not be certain until more of the wing is known. In the Midco collection there is a distal fragment of a wing which resembles that of *robustus* to a remarkable degree. I therefore place the species in *Sylvohymen* until more of its structure is known.

Sylvohymen ingens, n. sp.

Figure 7

Wing: length of fragment, 18 mm.; width, 9 mm.; estimated length of complete wing, 50 mm. Costal margin thickened distally, as far inward as R1; R1 diverging away from the margin only very slightly near the apex, with three short cross-veins between it and the margin; Rs with 4 branches, R2a, R2b, R3, and R4 + 5; a long cross-vein between R1 and

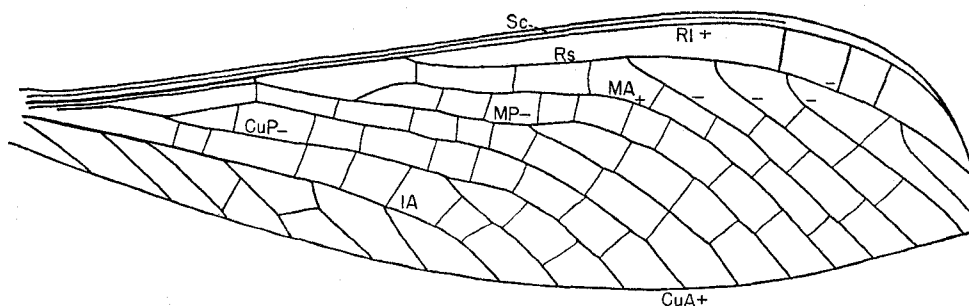


FIGURE 6. *Aspidothorax* sp. (Carboniferous of Commentry, France). Original drawing of fore wing, based on specimens in the Muséum National d'Histoire Naturelle, Paris. Lettering as in figure 1.

the fork of $R2 + 3$ and a shorter cross-vein near the apex between $R1$ and $R2$; one cross-vein between each branch of Rs ; two between $R4 + 5$ and MA .

Holotype: No. 4673ab Museum of Comparative Zoology; collected in Midco insect beds (loc. 3), Noble Co., Oklahoma (F. M. Carpenter and G. O. Raasch). This consists of the distal part of a wing. Since the preserved part does not include the origin of $R4 + 5$, it probably represents only about a third of the entire wing. This species was apparently only a little larger than *robustus*, which Martynov estimated to have a wing length of 40 mm.

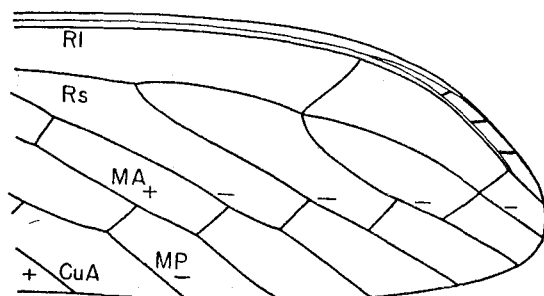


FIGURE 7. *Sylwohymen ingens*, n. sp. Drawing of holotype. Lettering as in figure 1.

The similarity between the venation of *robustus* and that of *ingens* is very striking, though of course the proximal parts of the wings may not have been so much alike. As Martynov points out, *Sylwohymen* (as far as known) is closer to *Bardohymen* than it is to any other Megasecoptera. Additional and more nearly complete specimens will be needed to make certain of this; if it should turn out that Rs is anastomosed with MA , as it is restored in Martynov's figure, the systematic position of the genus will be very different.

Family MARTYNOVIIDAE

This family has previously been known from the lower Permian of Kansas (Elmo), where it is represented by the genus *Martynovia*, with two species (*insignis* Till. and *protohymenoides* Till.). In the

Midco beds there are four new species, described below; one of these belongs to *Martynovia*, the others to new genera.

Genus *Martynovia* Till.

Martynovia Tillyard, 1932, Amer. Journ. Sci., **23**: 13; Carpenter, 1943, Proc. Amer. Acad. Arts Sci., **75**: 58.

In my discussion of this genus (1943), I stated that the radial sector included from 3 to 5 branches; since the number of branches of Rs in the new species is seven, the definition of the genus is now altered to that extent. In all other respects (so far as known) the following species conforms to the generic definition.

Martynovia longipennis, n. sp.

Figure 8

Fore wing: length, 20 mm.; width, 4.5 mm. Costal margin slightly concave basally, but with a distinct bulge above origin of MA ; rest of margin with slight convexity; posterior margin smoothly convex; base of wing more narrowed than in *protohymenoides*; apex of wing unknown; at least two prominent cross-veins in costal space, at the level or origin of CuP ; Sc weak distally, terminating at about mid-wing; $R1$ also very weak apically; both Sc and $R1$ apparently end in a faint pterostigma, as in *M. protohymenoides*; 4 or 5 well developed cross-veins between Rs and $R1$; Rs with seven branches, although this number is probably slightly variable in individuals; MA anastomosed for a short distance with Rs , much as in *insignis*; M arising from the stem of R in the manner characteristic of the genus, i. e., at the point of divergence of CuA from the same stem; CuP and $1A$ are like those of *protohymenoides*, but $2A$ is very short, having almost been lost by the narrowing of the base of the wing; two cross-veins present between MA , MP , CuP , and $1A$, and probably two also between the branches of Rs , though they are not preserved in the fossil.

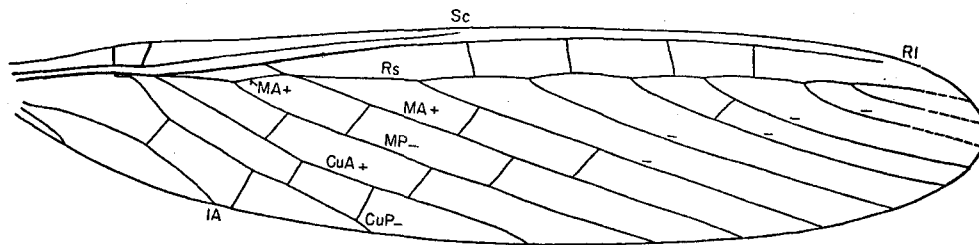


FIGURE 8. *Martynovia longipennis* n. sp. Drawing of fore wing (holotype). Lettering as in figure 1.

Hind wing unknown.

Holotype: No. 4676, Museum of Comparative Zoology; collected in the Midco insect beds (loc. 16), Noble Co., Oklahoma (F. M. Carpenter and G. O. Raasch). This is a well preserved wing, complete except for the very apex. The narrowness of the wing, especially basally, indicates that it is a fore wing.

Although this species has much longer wings than the genotype (*insignis*), its venation is essentially the same as that of the latter. In wing shape *longipennis* is similar to *protohymenoides*, but the greater number of branches of Rs and the very short 1A are obvious differences. The pterostigma of *longipennis* is not indicated by coloration; but the faintness of Sc and R1 distally shows that the pterostigma was present and formed essentially as in *protohymenoides*.

Eumartynovia, new genus

Fore wing: long and moderately slender. Costal space of normal width basally, but narrowed above end of Sc, at which point there is a pronounced bend in the margin of the wing; Rs arising almost at mid-wing and giving rise to four branches; M arising from the stem of R + M at the point of origin of CuA, as in *Martynovia*; MA anastomosing with Rs and also with R, well before the origin of Rs; MA, MP, CuA, CuP, and the anals all unbranched; cross-veins few in number. Pterostigma very long and colored, but not very thick.

Hind wing unknown.

Genotype: *Eumartynovia raaschi*, n. sp.

This genus, although close to *Martynovia*, is distinguished chiefly by having the costal margin distinctly indented at about mid-wing, and by having MA coalesced with the radius well before the origin of Rs.

Eumartynovia raaschi, new species

Figure 9; plate 2, figure 1

Fore wing: length, 22 mm.; width, 5 mm. Costal margin smoothly arched from the base to about the

middle of the wing; unevenly arched from mid-wing to apex; apex pointed; posterior margin smoothly curved; three pterostigmal cross-veins in costal area, two of them near the level of the origin of CuP, the other near the end of Sc; Sc ending at about mid-wing, slightly beyond the level of the origin of Rs; a heavily pigmented pterostigma extends from the end of Sc to slightly beyond the apex of the wing; this is confined to a narrow strip for most of its length, but near the fork of R2, it extends medially as far as R2 and R2a; between Rs and R1 there are three long cross-veins, and between the branches of Rs, as well as between MA, MP, CuA, CuP, and 1A there are two cross-veins; the free basal piece of MA is short, MA anastomosing with R1 so that R + MA is nearly equal in length to MA + Rs; 1A well developed, 2A short.

Holotype: No. 4680ab, Museum of Comparative Zoology; collected in the Midco beds (loc. 15-L), Noble Co., Oklahoma (F. M. Carpenter and G. O. Raasch). This species is named for Gilbert O. Raasch, who was first to find insects in the Midco strata. The holotype specimen is a strikingly preserved fore wing (plate 2, fig. 1).

This insect is remarkable for the long pigmented pterostigmal area. The species of *Martynovia* also have a long pterostigma, but so far as known in none of them is it as long or as heavily pigmented as in *raaschi*.

Phaneroneura, new genus

Allied to *Martynovia*. Fore wing: slender or moderately broad. Costal space of moderate width basally, narrowed at the level of origin of Rs; costal margin straight or nearly so; only one cross-vein apparently present in costal space; Rs arising just before mid-wing, with two or three branches; M arising from the stem of R + M at the point of separation of CuA from R + M, as in *Martynovia*; MA separating from MP very shortly after the origin of M, and anastomosing immediately with R, the free basal piece of MA being very short; R + MA longer than Rs + MA; MA, MP, CuA, CuP

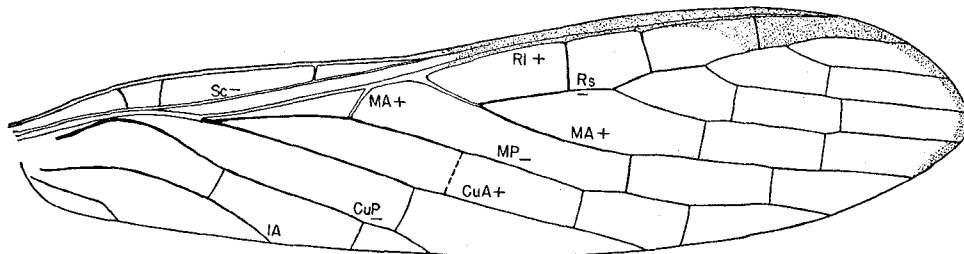


FIGURE 9. *Eumartynovia raaschi* n. sp. Drawing of fore wing (holotype). Lettering as in figure 1.

and anals all unbranched; cross-veins very few; pterostigma apparently formed as in *Martynovia*, unpigmented and weak.

Genotype: *Phaneroneura martynovae*, n. sp.

All the specimens of this genus being isolated wings, we have no knowledge of the differences, if any, between the fore and hind wings. Although some of the wings are slightly broader basally than others, none show the obvious differences in shape exhibited by the fore and hind wings of *Martynovia*.

This genus contains the most highly specialized *Martynoviids* so far known. The outstanding characteristics of the genus are the extensive anastomosis of MA with R, before the origin of Rs; and the reduction in the number of cross-veins and branches of Rs.

***Phaneroneura martynovae*, n. sp.**

Figure 10

Fore wing: length, 12.5 mm.; width, 3 mm. Costal margin nearly straight, with only a slight in-

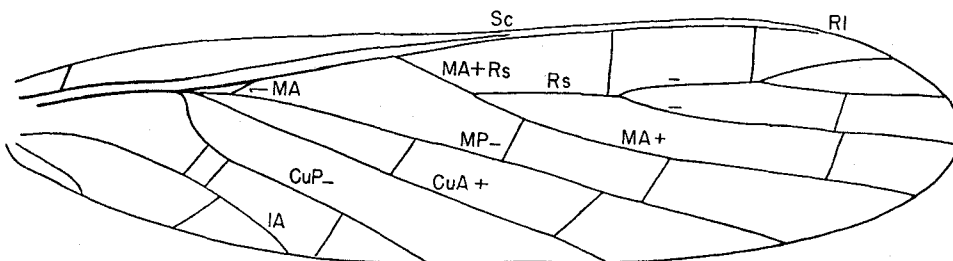


FIGURE 10. *Phaneroneura martynovae* n. sp. Drawing of fore wing based mainly on holotype. Lettering as in figure 1.

dication of concavity; apex narrowly rounded; costal space narrow at base, widest at level of origin of CuA; Sc weak distally, ending about mid-wing; pterostigma indicated only by a slight thickening of membrane; Rs forked twice, forming three branches, a strong cross-vein is present between Rs and R1 at each of these forks; R + M longer than MA + Rs; CuA nearly straight; CuP diverging abruptly away from the stem of Cu; 1A long, curved, 2A very short. Two cross-veins are present between most of main veins and branches of Rs, their arrangement slightly variable in individuals.

Holotype: No. 4675 ab, Museum of Comparative Zoology; collected in Midco insect beds (loc. 15-L), Noble Co., Oklahoma (F. M. Carpenter and G. O. Raasch). This is a well preserved and complete wing.

Paratypes: No. 4738, Museum of Comparative Zoology same collecting data as holotype, except for quarry no. 8-M. This specimen is also a complete wing, with a venation almost identical with that of

the holotype. It may be a hind wing, however, since the posterior margin is slightly more rounded basally, and the origins of M, CuP and CuA are nearer the base than in the holotype. No. 4670, same collecting data (loc. 15-L); this is a nearly complete wing, lacking the proximal fifth of the wing.

In addition to these, there are three more poorly preserved specimens: No. 4739 (loc. 15-L); no. 4740 (loc. 8-M); and no. 4677ab (loc. 15-L). The last specimen consists of the distal half of a wing 3.5 mm. wide; this may be a hind wing.

This species has been named for Olga Martynova, who worked on fossil insects for many years with her husband, Dr. A. B. Martynov, and who has continued her studies independently since his death in 1938.

***Phaneroneura reducta*, n. sp.**

Figure 11

Fore (?) wing: length, 7 mm.; width, 2.5 mm. Costal margin almost straight, as in the genotype;

apex broadly rounded; posterior margin strongly and evenly curved; costal space relatively broader above origin of CuA than in *martynovae* and more abruptly narrowed at end of Sc; Sc terminating at the middle of the wing; pterostigma very weakly indicated by slight thickening of membrane; Rs with but one fork though in the holotype only there is a weak incomplete vein running from R2 + 3 towards the end of R1; one cross-vein between Rs and R1, at the fork of Rs; MA + R much longer than MA + Rs; CuP not so abruptly diverging from the base of Cu as in *martynovae*, arising from the stem just proximad to the point of separation of MP and CuA (at least in holotype); 1A long; only one cross-vein between the main veins of the wing, and none at all between R2 + 3 and R4 + 5.

Holotype: No. 4733ab, Museum of Comparative Zoology; collected in Midco insect beds (loc. 15-L), Noble Co., Oklahoma (F. M. Carpenter and G. O. Raasch). This specimen consists of an excellently preserved wing, complete except for the very base.

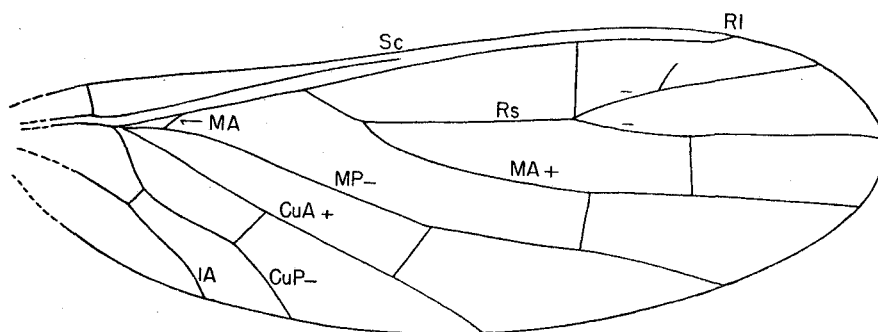


FIGURE 11. *Phaneroneura reducta*, n. sp. Drawing of wing, based mainly on holotype. Lettering as in figure 1.

Paratypes: No. 4737ab, Museum of Comparative Zoology; same collecting data (loc. 15-L); this is also nearly a complete wing, lacking only the very base; its venation is identical with that of the holotype, except for the absence of the adventitious vein from R2 + 3. No. 4741ab, same data (loc. 15-L); this is a well preserved wing lacking more of the base than the other specimens; it is 6 mm. long and 2.5 mm. wide; R2 + 3 lacks the adventitious vein.

The three specimens on which this species is based may be hind wings and I have considered the possibility that they might represent the hind wing of *martynovae*. However, in none of the other Martynoviidae or in fact in none of the Megasecoptera as a whole so far known, do the fore and hind wings differ in venation, except of course for slight contour of the veins, etc. The specimens of *reducta* are distinctly different in venation from those of *martynovae*: Rs has only one fork instead of two, and there is only one cross-vein between all main veins, instead of two. Furthermore, the wings of *reducta* are only about half the size of those of *martynovae*, a difference which is not known to occur between the fore and hind wings of Megasecoptera. It is my conviction therefore, that even if these specimens are hind wings, they do not belong to *martynovae*.

Family Protohymenidae

This family has previously been found in the Permian of Kansas and Russia. In the Oklahoma collection it is represented by four new species and one (*Protohymen reardi* Carp.) already described from the Elmo limestone. Before discussing these species, however, I wish to consider certain venational aspects of the Protohymenidae which need clarification. The homologies of the wing veins of the Carboniferous Megasecoptera have been generally agreed upon, for although in some genera there is slight venational anastomosis, the identity of all main veins is obvious. This is also true of the vena-

tion of most Permian genera, in spite of the increased amount of anastomosis; and the interpretation which I proposed (1931) for such specialized genera as *Protohymen* and *Permohymen* has been generally accepted (Tillyard, 1936, p. 447). Martynov, although accepting this view in relation to other views, advocated a very different interpretation of the structure of Rs. He believes that the condition of the radius in *Eohymen* Mart. (1937) and *Aspidohymen* Mart. (1930) represents an early stage in the evolution of this vein, ultimately leading to its structure in the Protohymenidae. In *Aspidohymen*, according to Martynov, Rs divides early into a distal branch (Rsds) and a proximal branch (Rspr); the former arises from the stem of Rs, then anastomoses with R1, only to branch off again distally. In *Eohymen* the anastomosis of Rsds with R1 takes place further proximally, so that it appears to arise directly from R1. The amount of anastomosis of Rsds with R1 has increased during the subsequent evolution of the Protohymenoptera; in *Protohymen*, the origin of Rsds from R1 is at the level of the pterostigma; and in *Asthenohymen* the coalescence is complete. It is on the basis of the coalescence of these veins that Martynov separates the Protohymenoptera from the Order Megasecoptera, in which there has been no such anastomosis.

I have two main objections to this proposal. In the first place, the evidence provided by *Aspidohymen* and *Eohymen* is very questionable. *Aspidohymen* is known by two species, *extensus* Mart. (1930, 1937) and *chopardi* Zal. (1937) from the Russian Permian.³ Both of these species are based on unique wings, each lacking the proximal third. We have no knowledge, therefore, of the origin of any main veins except Rs. The part of the venation that is known is different in several respects from

³ Only *extensus* was known to Martynov, *chopardi* having been described just before his death.

that of the Protohymenidae and related families. In both species of *Aspidohymen*, for example, MA is forked (convex),⁴ though it is simple in all other families which have been placed in the Protohymenoptera; and Rs (Rspr of Martynov) is unbranched, another feature not occurring in other Protohymenoptera.⁵ Furthermore, I am convinced that Martynov has not correctly homologized certain veins in *Aspidohymen*. He does not indicate in his figure of *extensus* whether the distal branch of Rs (Rsds) is convex or concave; probably its nature was not suggested in the poorly preserved type. But Zalessky's figure of *chopardi*, which is based on a better fossil shows this vein to be convex (+), not concave. It cannot therefore be a branch of the concave Rs.

The genus *Eohymen* is also based on a poorly preserved wing, as indicated by the broken and dotted lines in Martynov's figure (1937, fig. 1). There are many features of the preserved part of the wing which are entirely foreign to the Protohymenidae, etc., such as the double row of cells between certain veins and the remoteness of R from the costal margin. Martynov presents no evidence showing that this wing is actually related to the Protohymenidae, but even if we assume that it is, the gap between it and *Protohymen* is too great for it to be taken as the basis of the explanation of the protohymenid wing.

The Protohymenidae, also, furnish evidence which refutes Martynov's theory of the protohymenopterous venation. A detailed examination of the pterostigmal area of *Protohymen* shows R1 running along the posterior edge of the pterostigma. After giving rise to the vein *a* (figure 12A), it appears to continue for a short distance along the pterostigma (b). A similar condition occurs in all species of the genus, with but slight variation. The pterostigmal area of *Permohymen* is obviously of the same general type. Now Martynov identified the vein *a* as the reduced distal branch of Rs (Rsds),

but he apparently overlooked the fact that this vein is distinctly convex, as shown in my figure of *permianus* (1930, fig. 1). The convexity of this vein is clearly indicated in all well preserved specimens of *Protohymen*, especially in those of the Midco beds. It can only be R1, therefore, not a part of Rs (concave).

For the foregoing reasons I believe that Martynov's interpretation of the protohymenid venation is based on doubtful evidence and has more facts against than for it. A simpler and more direct explanation of the pterostigmal area in the Protohymenidae was contained in my first paper on the Protohymenoptera (1930) but was overlooked by Martynov. The suggestion was made there that the apparent anterior "branch" of R1 (*b* in figure 12) might be a modified cross-vein. An ob-

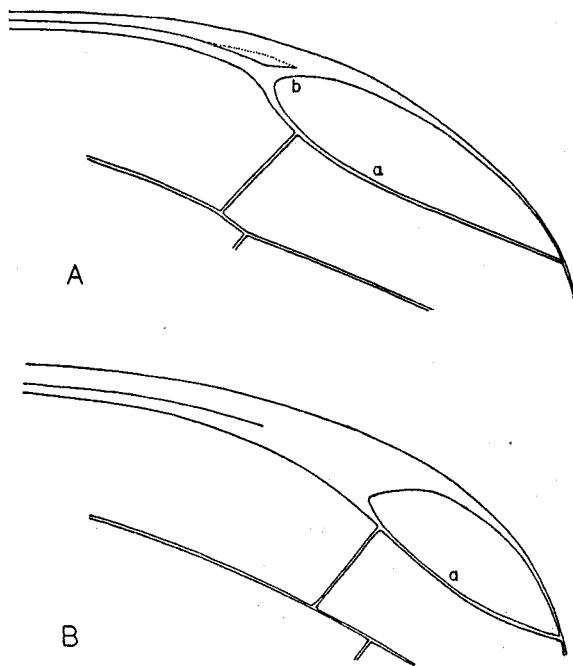


FIGURE 12. Pterostigmal area. *Protohymen venustus*, n. sp. (A); and *Permohymen schucherti* Till. (B), from the Lower Permian of Kansas. For lettering see text.

lique cross-vein actually does occur at this point in many Megasecoptera, though it is usually weakly preserved. A slight change in the angle of inclination of this cross-vein, together with the thickening of the pterostigma, would produce the condition found in *Protohymen*.

Genus *Protohymen* Till.

Protohymen Tillyard, 1924, Amer. Journ. Sci. (5) 8: 114; Carpenter, 1930, Psyche, 37: 349.

⁴ In spite of the convexity of both branches of MA, Martynov identified the anterior one as Rs4.

⁵ It should be noted that the nature of the origin of Rs in *Aspidohymen* is uncertain. In his original drawing of *extensus* Martynov showed three thin lines above his Rs (at origin of Rs); in my copy of his figure (1930, fig. 4), I omitted the posterior one of these three, being under the impression that two of the lines represented the width of R. Martynov called attention to this omission (1937, p. 63) and stated that only by omitting that vein would my interpretation be possible. However, Zalessky's later figure of *chopardi* shows no such vein there in his better preserved fossil, his drawing being exactly like my copy of Martynov's in that respect.

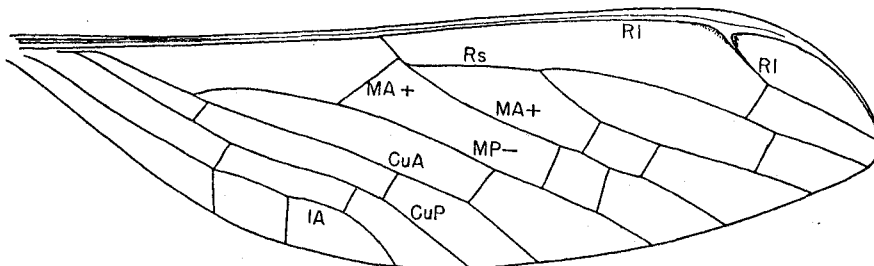


FIGURE 13. *Protohymen curvatus*, n. sp. Drawing of fore wing (holotype). Lettering as in figure 1.

***Protohymen curvatus*, new species**

Figure 13

Fore wing: length, 12 mm.; width 3.5 mm.; wing membrane distinctly uneven, the center of the cells of the wing bulging slightly above the edges. Costal margin straight or nearly so, as far as the middle of pterostigma; apex pointed, the tip of the wing more posterior than anterior; posterior margin strongly curved for its entire length; Sc and R1 as in *permianus*; MA anastomosed with Rs for a very short distance only; 1A more remote from the margin than in *permianus*, especially distally; rest of venation essentially as in *permianus*.

The hind wing of this insect is apparently represented by a wing (no. 4665) 14 mm. long and 3.9 mm. wide; its shape is like that of the specimen just described, except that the anal margin is more broadly rounded.

Holotype: No. 4666ab, Museum of Comparative Zoology; collected in Mideo insect bed (loc. 8-M), Noble Co., Oklahoma (F. M. Carpenter & G. O. Raasch). This is a complete and splendidly preserved wing. Paratype: No. 4665ab, Museum of Comparative Zoology; same collecting data; it is a complete wing with a more broadly rounded anal margin than the holotype, but with an identical venation, except for the position of the cross-veins.

In addition to these specimens there are two others, not so well preserved; no. 4686ab (loc. 15-L),

a hind (?) wing; and no. 4683 (loc. 12-M), a fore (?) wing.

Although the wing of *curvatus* resembles that of *permianus* in general form, it differs chiefly in having the posterior margin curved for its entire length, and in having a more sharply pointed apex. The wing membrane of *curvatus* is curiously uneven. The occurrence of this peculiarity in all specimens of *curvatus* shows that it is not an individual condition or the result of unusual preservation. Viewed under oblique light the membrane forms a series of shallow bulges and depressions. No other protohymenid possesses this characteristic, except the following new species (*latus*).

***Protohymen latus*, new species**

Figure 14

Hind (?) wing: length, 15 mm.; width, 4.2 mm.; wing membrane uneven, as in *curvatus*; shape of wing much like that of *curvatus*, but anal margin more broadly rounded; costal margin nearly straight for most part, but starting to curve somewhat before the beginning of the pterostigma; apex slightly more rounded than in *curvatus*; posterior margin curved for its entire length; Sc and R1 as in *permianus*; MA anastomosed with Rs for a very short interval; 1A very remote from posterior margin, especially distally; a cross-vein present between 1A and margin near base of wing, and one at about the

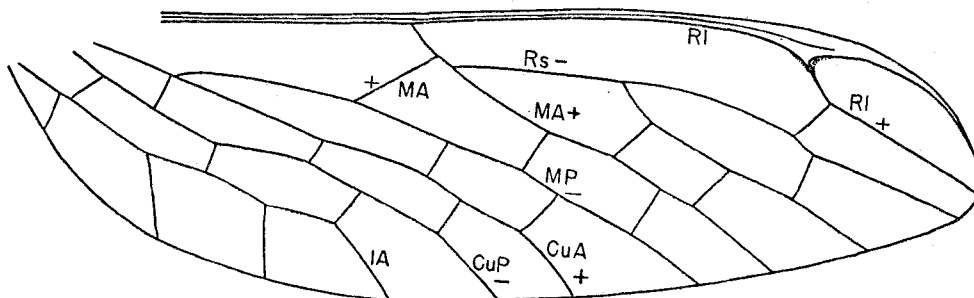


FIGURE 14. *Protohymen latus*, n. sp. Drawing of holotype. Lettering as in figure 1.

same level between CuP and 1A. Rest of venation as in *permianus*.

Holotype: No. 4667, Museum of Comparative Zoology, collected in Midco insect bed (loc. 8-M), Noble Co., Oklahoma (F. M. Carpenter and G. O. Raasch). This is a well preserved wing, complete except for the very base of the costal margin. The broadly rounded posterior margin suggests that it is a hind wing and it may eventually turn out to belong to *curvatus*. Both *curvatus* and *latus* have 1A more remote from the margin than it is in any other *Protohymen*; but in *latus* the distance between that vein and the margin is so much greater than in *curvatus* that I believe *latus* to be a distinct insect. The remoteness of 1A from the margin is interesting phylogenetically because it approaches the structure of certain Carboniferous Megasecoptera. The proximal cross-veins between 1A and the margin and CuP and 1A may be individual traits only, but I have not seen them in other specimens of the genus.

***Protohymen venustus*, new species**

Figure 15

Fore (?) wing: length, as preserved. 11 mm.; estimated length of complete wing, 12.5 mm.;

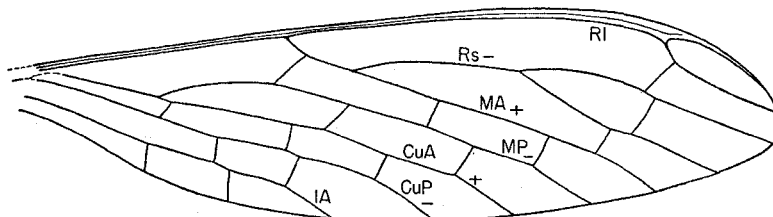


FIGURE 15. *Protohymen venustus*, n. sp. Drawing of holotype. Lettering as in figure 1.

width, 2.8 mm. Membrane smooth, as in *permianus*; slenderly oval in shape; costal margin straight only to the proximal end of the pterostigma, the apical curvature beginning at this point; apex acute; posterior margin regularly curved for its entire length; Sc and R1 as in *permianus*; pterostigma not so broad as in *permianus* and *curvatus*; MA coalesced with Rs for a longer interval than in *curvatus*; rest of venation as in *permianus*. Hind wing unknown.

Holotype: No. 4668, Museum of Comparative Zoology; collected in the Midco insect beds (loc. 15-L), Noble Co., Oklahoma (F. M. Carpenter and G. O. Raasch). This is a splendidly preserved wing, complete except for the very base.

This graceful wing differs from that of the described species of *Protohymen* in having the apex of the wing nearly symmetrically curved. In other respects the shape of the wing is more like that of

curvatus than of *permianus*, but it is narrower proximally and the membrane is decidedly smooth, as in *permianus*.

***Protohymen largus*, new species**

Figure 16

Fore wing: length as preserved, 18.5 mm.; estimated complete length, 21.5 mm.; width, 4.8 mm.; membrane smooth; costal margin straight as far as the beginning of the pterostigma, the apical curvature beginning at that point; apex nearly symmetrical; middle part of posterior margin straight; Sc and R1 as in *permianus*; pterostigma narrower than in *permianus* and *curvatus*; MA anastomosing with Rs for a very short distance; 1A close to hind margin, as in *elongatus* Carp.; rest of venation as in *permianus*. Hind wing unknown.

Holotype: No. 4671, Museum of Comparative Zoology; collected in the Midco insect beds (loc. 15-L), Noble Co., Oklahoma (F. M. Carpenter and G. O. Raasch). There is a second, more poorly preserved specimen in the collection, no. 4672ab (loc. 12-U); it has a wing length of 15 mm. and a width 13.5 mm.

This is the largest species of *Protohymen* known;

its wing expanse was obviously about 45 mm., whereas that of *permianus* was not over 30 mm. In size and shape the wing approaches that of *elongatus* Carp., from Elmo limestone, but the latter has a pointed and very asymmetrically curved apex, whereas that of *largus* is rounded and nearly symmetrical.

***Protohymen readi* Carp.**

Protohymen readi Carpenter, 1933, Proc. Amer. Acad. 68: 425.

One specimen (no. 4679) which appears to be this species is also included in the Oklahoma collection. The wing is 15 mm. long and 3.5 mm. wide and it lacks only the very base. It has the strong cross-vein proximal to the pterostigma as in *readi*, as well as the very pointed apex of the latter. This is the only species of the family Protohymenidae in the col-

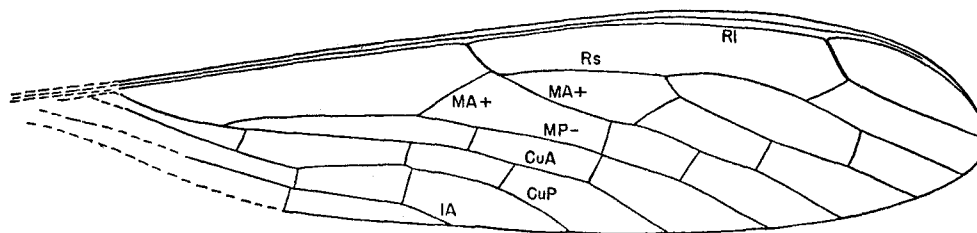


FIGURE 16. *Protohymen largus*, n. sp. Drawing of fore wing (holotype). Lettering as in figure 1.

lection at hand which appears to be common to the Elmo and Midco insect beds.

FAMILY ASTHENOHYMENIDAE

These are the most abundant of the Megaseoptera in the Midco beds, so far as the number of individuals is concerned. Slightly more than a hundred specimens are included in the present collection. All of these belong to *Asthenohymen*, the only genus of the family known. A careful study of this material, during which drawings were made of about a third of the specimens, shows that four new species are included, in addition to *A. dunbari* Till. and *A. pusillus* Till., both originally described from the Elmo beds in Kansas. Because of the uniformity of the venation in this genus, the species have been based almost entirely on the shape and size of the wings. It is of course probable that each of these species actually consists of several species, differing from each other in details of body structure, such as genitalia; but we are obviously unable to make such distinctions in the fossils.

Three of the new species described below are unfortunately known only by isolated wings. Presumably, however, the fore and hind wings of these species differ from each other in much the same way as those of *dunbari* and *apicalis*, n. sp., of which complete specimens are known, i. e., the anal margin of the hind wing is slightly more broadly rounded than that of the fore wing and the costal space is somewhat narrower.

Study of the new Asthenohymenidae has convinced me that my previous interpretation of the structure of the radial sector requires modification. In my original account of the venation of these insects (1930), I was led to conclude, by analogy with the Protohymenidae, that MA was coalesced with Rs much as in the latter, except that the free piece of MA had become transversely arranged, more or less at a right angle to Rs, so as to resemble a cross-vein. This interpretation seemed certain to be correct in view of the condition in the Protohymenidae, which were generally considered very closely related

to the Asthenohymenidae, and it was accepted by Martynov, Tillyard, and other students of fossil insects. I now believe that, although MA is certainly anastomosed with Rs, the transverse vein mentioned is not part of MA. A comparison of the figures of the Martynoviidae (Figure 17), especially *Phaneroneura*, with those of *Asthenohymen*, will make clear my present interpretation of the latter. There is a striking resemblance between the venation of *Phaneroneura* and that of the Asthenohymenidae; and the differences are in all cases due to specialization on the part of *Asthenohymen*, except for the number of cross-veins. The most significant feature of the Martynoviidae is the nature of the anastomosis between Rs and MA. In *M. longipennis*, the amount of coalescence is very slight—in fact MA hardly more than touches Rs. In *Eu. raaschi*, MA joins R well before the origin of Rs; and in *Phaneroneura* Rs joins R much nearer the base of the wing. In view of the similarity between the venation of *Asthenohymen* and *Phaneroneura*, it now seems to me that the condition in the latter represents a stage through which the asthenomenid wing has passed. Hence, the real base of MA in *Asthenohymen* has been completely lost by the proximal migration of its origin; and the transverse vein which has previously been thought to be part of MA is really only a cross-vein. In this connection it is noteworthy that in many specimens of *Asthenohymen* the cross-vein indicated is distal of the point of separation of MA from Rs (see Carpenter, 1930, fig. 4). It is of course true that the number of cross-veins in *Phaneroneura* is not quite so large as in *Asthenohymen*; but it is extremely improbable anyway that *Phaneroneura* itself gave rise to the Asthenohymenidae; in all probability a related genus, with a similar structure of Rs and with more cross-veins, was in the direct line of ancestry.

It follows from the foregoing discussion, of course, that the Asthenohymenidae are not at all closely related to the Protohymenidae. This is of interest because it substantiates the evidence provided by the position of the wings at rest in the two families.

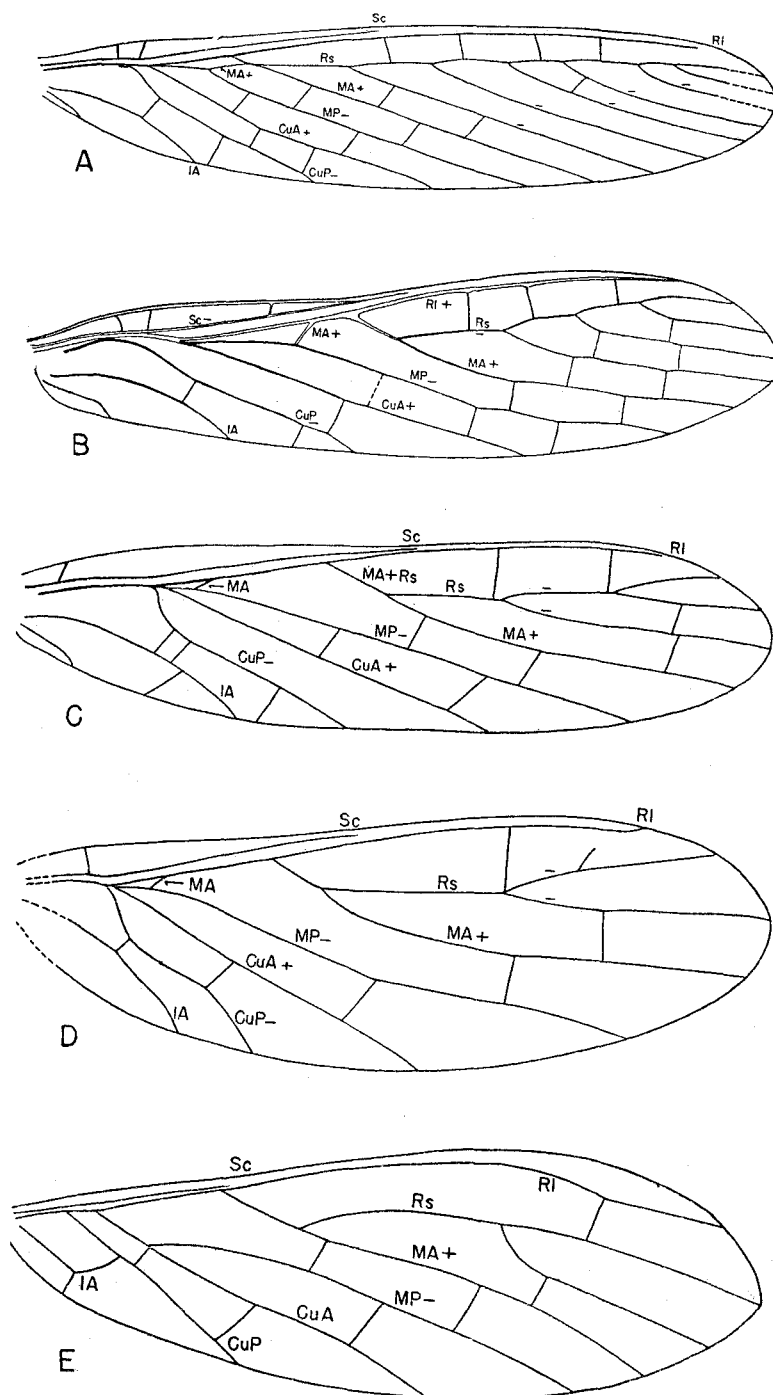


FIGURE 17. Comparison of venation of Martynoviidae and Asthenohymenidae. A, *Martynovia longipennis*, n. sp. (Martynoviidae); B, *Eumartynovia raaschi*, n. sp. (Martynoviidae); C, *Phaneroneura martynovae*, n. sp. (Martynoviidae); D, *Phaneroneura reducta*, n. sp. (Martynoviidae); E, *Asthenohymen apicalis*, n. sp. (Asthenohymenidae). Lettering as in figure 1.

The Asthenohymenidae are known to have been able to fold their wings back over the abdomen at rest, whereas the Protohymenidae were apparently not able to do so. I have discussed this question in my account of the Carboniferous Prochoropteridae (1940), which were also able to fold their wings over the abdomen, and have pointed out there that although at first glance the Asthenohymenidae did not seem at all closely related to the Prochoropteridae, the ability to fold the wings probably did not arise independently in the two families. According to the new interpretation of the asthenohymenid venation, however, the Prochoropteridae and Asthenohymenidae are really very close relatives.

Genus *Asthenohymen* Till.

Asthenohymen Tillyard, 1924, Amer. Jour. Sci. 8: 117; Carpenter, 1939, Proc. Amer. Acad. Arts Sci. 73: 31.

***Asthenohymen triangularis*, new species**

Figure 18

Fore wing: length, 10 mm.; width, 3 mm. Proximal part of wing much narrower than the distal part,

The wings of this species are more nearly triangular in shape than those of *dunbari* or *pusillus*. The width of the wing at the level of the origin of CuA is 1.2 mm., whereas the maximum width is 3 mm., or 2.5 times the basal width. The size of the holotype is greater by about 2 mm. than that of any *dunbari* which I have seen from either the Elmo or Midco beds.

***Asthenohymen apicalis*, new species**

Figure 19

Fore wing: length, 7.5 mm.; width, 2.5 mm. Proximal part of wing only moderately wider than the basal part; costal margin very nearly straight, with only a slight bulge at the level of the origin of CuP; apex distinctly pointed, the apical curvature beginning before the level of the pterostigmal cross-vein; posterior margin at least slightly curved for its entire length; R1 slightly curved away from margin at pterostigma; pterostigma distinctly darker than the rest of the membrane; 2A short, as in *triangularis*; venation in other respects like that of *dunbari*.

Hind wing: similar to fore wing in size, venation

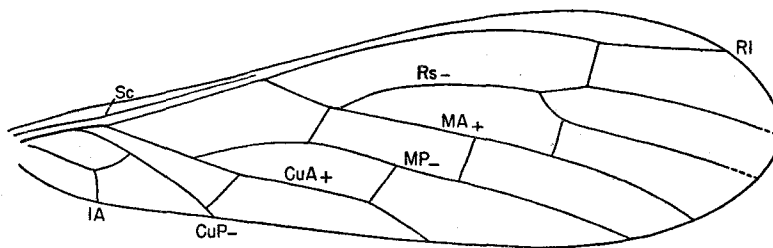


FIGURE 18. *Asthenohymen triangularis*, n. sp. Drawing of fore wing (holotype). Lettering as in figure 1.

the wing as a whole being narrowly triangular; costal margin very nearly straight, with a slight bulge above the origin of CuP; apex rounded, the apical curvature beginning at about the pterostigmal cross-vein; posterior margin nearly straight at the middle part; R1 slightly curved away from margin at pterostigma; pterostigma not perceptibly pigmented in type; 2A short, as in *pusillus*; venation in other respects like that of *dunbari*.

Holotype: no. 4717, Museum of Comparative Zoology; collected in the Midco insect beds (loc. 15-L), Noble Co., Oklahoma (F. M. Carpenter and R. O. Raasch). This specimen consists of a complete and splendidly preserved wing; its narrowed anal region indicates that it is a fore wing. In addition to the type there are two other specimens (nos. 4716, 4743) which have a wing-shape like that of the holotype, but the length of the wings is only 6 mm.

and shape (including pointed apex), but anal region is slightly broader.

Holotype: no. 4722, Museum of Comparative Zoology; collected in Midco insect beds (loc. 15-L), Noble Co., Oklahoma (F. M. Carpenter and G. O. Raasch). This consists of a splendidly preserved and complete fore wing; no. 4700 (loc. 15-L), a complete fore wing; no. 4705 (loc. 31), a complete fore wing; no. 4710, a complete hind wing; no. 4721 (loc. 15-L), a complete hind wing; No. 4744 (loc. 15-L), a nearly complete fore wing; no. 4745 (loc. 4-L), a complete fore wing; no. 4783 (loc. 8-M), a complete specimen, with parts of all wings, thorax and abdomen; the body is 12 mm. long, which is about one and a half times the length of *dunbari*. The eyes seem more protuberant than in *dunbari*, though preservation may be the cause of this difference.

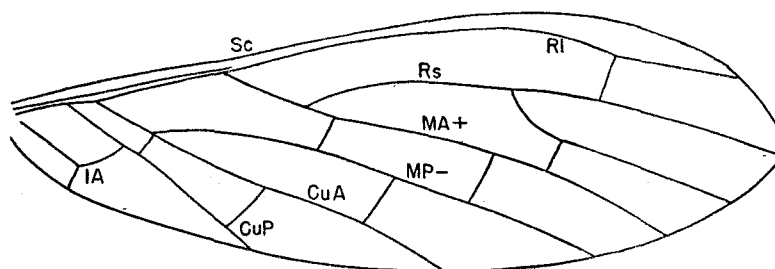


FIGURE 19. *Asthenohymen apicalis*, n. sp. Drawing of fore wing, based mainly on holotype. Lettering as in figure 1.

This species is distinguished from *dunbari* and other described members of the genus by the pointed apex and strongly curved posterior margin. It is the commonest species of *Asthenohymen* in the Midco beds, next to *dunbari*, there being ten other specimens (nos. 4746 or 4727) in the collection in addition to the types. I have identified specimens nos. 4721 and 4710 as the hind wings of this insect because they differ from the holotype just as the fore and hind wings of *dunbari* differ.

***Asthenohymen parvulus*, new species**

Figure 20

Fore wing: length, 4.3 mm.; width, 15. mm. Distal part of wing much broader than proximal part; costal margin nearly straight, with a slight bulge over the origin of CuP; distal margin of wing broadly curved, but the very apex is pointed; R1 curved away slightly from the margin at pterostigma; 2A close to hind margin and very short, the curved cross-vein joining it to 1A being fully as long as the part of 2A from the cross-vein to the base; venation in other respects as in *dunbari*.

Hind wing: a specimen which I have identified as the hind wing of this species is 4.2 mm. long and 1.5 mm. wide and has more or less rounded anal margin; in other respects it is similar to the fore wing.

Holotype: No. 4747, Museum of Comparative Zoology; collected in the Midco beds (loc. 15-L), Noble Co., Oklahoma (F. M. Carpenter and G. O. Raasch). This specimen is a remarkably well pre-

served and complete fore wing. Paratypes: No. 4698 (loc. 15-L); this is a complete hind wing, well preserved; No. 4711 (loc. 15-L), a complete fore wing having the same size, shape and venation as the holotype.

This insect, which could not have had a wing expanse of more than 10 mm., is the smallest Megasecopter known. The wings are shaped somewhat like those of *triangularis*, but are less than one-half as long and of course have a pointed apex. The narrowed anal area of the fore wing has brought 2A closer to the wing margin than in other known species of the genus.

***Asthenohymen latus*, new species**

Figure 21

Fore wing: length 7 mm., width 2.2 mm. Costal margin of wing nearly straight, only a slight bulge above origin of CuP; posterior margin strongly curved for its whole length; apex rounded, but the very tip pointed; wing broadest just beyond middle; R1 strongly curved away from margin at pterostigma; pterostigma strongly pigmented in holotype; Cu2 extremely short, the cross-vein connecting it to 1A being closer to the base of CuA than in other species. Hind wing: similar to the fore wing, but with slightly more rounded anal margin; the specimen identified as a hind wing has a length of 7 mm. and width, 2.5 mm.

Holotype: no. 4720, Museum of Comparative Zoology; collected in Midco insect beds (loc. 15-L),

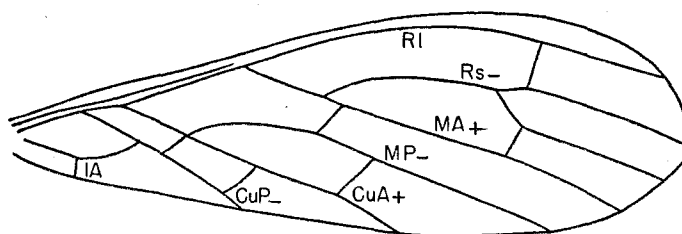


FIGURE 20. *Asthenohymen parvulus*, n. sp. Drawing of fore wing (holotype). Lettering as in figure 1.

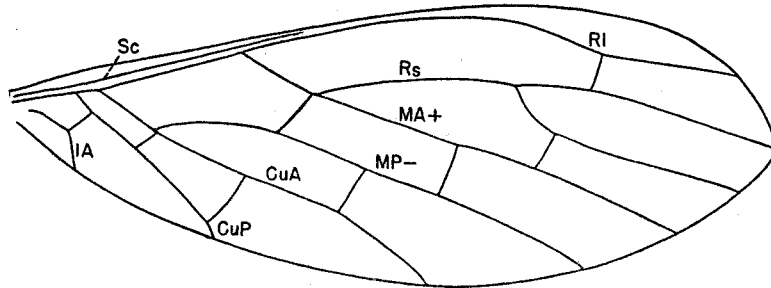


FIGURE 21. *Asthenohymen latus*, n. sp. Drawing of fore wing (holotype). Lettering as in figure 1.

Noble Co., Oklahoma (F. M. Carpenter and G. O. Raasch). This is a very well preserved and complete fore wing. Paratypes: no. 4702 (loc. 15-L), a complete fore wing; no. 4782 (loc. 8-M), a complete hind wing.

This species resembles *apicalis* in having the strongly curved posterior margin, but the extreme width of the wing is unique, as is also the basal part of the cross-vein between 1A and 2A.

Asthenohymen dunbari Till.

Asthenohymen dunbari Tillyard, 1924, Amer. Jour. Sci. 8: 117; Carpenter, 1939, Proc. Amer. Acad. Arts Sci. 73: 31.

In the Midco collection there are about forty well preserved specimens which appear to be identical with *dunbari*, originally found in the Elmo limestone. All of these specimens consist of isolated wings and it is of course possible that the Oklahoma specimens differed from those in the Elmo limestone in body structure (e. g. genitalia); but until evidence to the contrary has been found, I consider them to be *dunbari*.

Asthenohymen pusillus Till.

Asthenohymen pusillus Tillyard, 1926, Amer. Jour. Sci. 11: 68; Carpenter, 1933, Proc. Amer. Acad. Arts Sci. 68: 429.

Seven specimens of this insect are present in the Oklahoma collection. As I have pointed out in the case of *dunbari*, we have no way of knowing whether or not the body structure differed from that of the Kansas material. It is interesting to note that *pusillus* is rarer than *dunbari* in both the Elmo and Midco beds.

THE VENATION AND RELATIONSHIPS
OF THE MEGASECOPTERA

The term "Megasecopterida" was first used by Brongniart (1885) for a "family" of several genera from the Carboniferous of France and England. This group he originally (1885) placed in his Order Pseudo-Neuroptera, together with the Protodonata

and Protephemmerina; but later (1894) he assigned it to the "Neuropteroid series" of the Order Palaeodictyoptera. Handlirsch subsequently (1906) elevated the Megasecopterida to an order, changing the name to Megasecoptera. Additional Carboniferous genera, including four from North American deposits, have been referred to the order by Scudder, Handlirsch, Meunier, and Carpenter. The first Permian Megasecoptera (*Prothymen*, *Permohymen* and *Asthenohymen*) were found in Kansas and described by Tillyard (1926) in a new order, Protohymenoptera, considered by him ancestral to the Hymenoptera. Other representatives of this group, subsequently collected in the Kansan and Russian Permian, furnished evidence that the Protohymenoptera were really closely related to the Megasecoptera and could be considered a suborder within it. During the past twenty years sixteen more genera of Permian Megasecoptera have been described, some being obviously allied to the Protohymenoptera, and others to the Carboniferous or Eumegasecopterous families. It has now become apparent that the Order Megasecoptera, instead of being primarily a Carboniferous order, did not attain its maximum development until the Permian Period. The interrelationships of these Permian and Carboniferous genera have not been at all clear, and the whole picture of the order has been most confused; but some of the recently discovered fossils, including those described above, have indicated what appears to be the general pattern of evolution within the order, and, at the same time, have raised broader questions of the relationships between the Megasecoptera and other orders.

When, in 1926, Tillyard described the so-called Protohymenoptera from the Kansan Permian, he noted that although the Protohymenidae (*Prothymen* and *Permohymen*) were always preserved with their wings outspread, i. e., in the usual palaeopterous condition, the *Asthenohymenidae* were preserved with their wings folded over the abdomen, i. e. in the usual neopterous condition. He later

(1936) elaborated on the significance of this difference, and concluded that, "It must now be evident that a group of insects, the Order Megasecoptera, which began as Palaeoptera, have within the limits of a single small derived group, the Protohymenoptera, evolved into a highly specialized Neopterous type, the family Asthenohymenidae! I do not suppose that anybody will attempt to claim that *Asthenohymen* should be separated from its obvious relatives, *Protohymen* and *Permohymen*, which rested with their wings outspread, in order to preserve the two subdivisions Palaeoptera and Neoptera, which are now seen to cut across the actual phylogeny of these ancient groups. The only logical course is to suppress the two groups Palaeoptera and Neoptera, and adopt a classification more in keeping with the facts.

"Surely it must have been obvious for a long time that all Neoptera have been derived from extinct Palaeopterous types. Now the fossil record shows us a group, Protohymenoptera, of either ordinal or subordinal rank, whichever you prefer, in which the change is seen actually taking place . . . My conclusion is that the Order Protohymenoptera shows affinities with both the Megasecoptera and Hymenoptera. It should be regarded as a specialized offshoot from the common ancestor of the Megasecoptera and the Odonatoid complex . . . and, at the same time, as a remnant of the group from which the Hymenoptera have been evolved."

I have quoted these two paragraphs because they were Tillyard's last statements relative to the Protohymenoptera and because of their broad phylogenetic implications. If I understand these remarks correctly, Tillyard contends (1) that the neopterous condition is of polyphyletic origin, and (2) that the Hymenoptera are derived, through the Protohymenoptera, from the common ancestors of the Megasecoptera and the odonatoid complex. It is to be noted that no mention is made of the Neuroptera, Mecoptera, and other holometabolous insects which are usually regarded as close relatives of the Hymenoptera. However, in 1932 (p. 23) Tillyard remarked that if the Protohymenoptera should turn out to be "descended from Megasecoptera, then we may also have to reconsider Handlirsch's view that the Neuroptera are similarly derived."

Since the above articles were written, several fossils have been found which indicate that the origin of the neopterous condition in the Protohymenoptera is not so simple as Tillyard supposed. Tillyard himself subsequently described (1937) another Megasecopteran (*Elmoa*) from the Kansas Permian, representing a new family and in his opinion a rem-

nant of a very old megasecopterous group. This insect subsequently turned out (Carpenter, 1943) to have the neopterous wing condition, like *Asthenohymen*. Furthermore, certain Carboniferous genera are now known to share the same characteristic—two American genera of the family Prochoropteridae (Carpenter, 1943) and the genus *Diaphanoptera*, from France (Brongniart, 1885). Other related families, as the Martynoviidae, were almost certainly similarly neopterous, although, since no complete specimens have been found, we have only indirect evidence of it.

Such a series of forms at once suggests that the ability to fold the wings over the abdomen, instead of being developed independently by the Permian Asthenohymenidae, arose in a more ancient and generalized stock. This conviction is strengthened by the obviously close relationship between the groups mentioned. A comparison of the wings of the Elmoidae, Martynoviidae and Asthenohymenidae reveals several striking characteristics common to all. The most obvious of these is the proximal convergence of the strongly convex CuA and R, forming an angle bisected by the stem of M; another is the relative remoteness of R1 and Sc from the costal margin, as contrasted with the position of these veins in the Protohymenidae. I have shown above, under the account of the Asthenohymenidae, that the venation of this family can best be explained by comparison with that of the Martynoviids, not with that of the Protohymenids. It is therefore my conviction, on the basis of the evidence now at hand, that the families mentioned (Diaphanopteridae, Prochoropteridae, Elmoidae, Martynoviidae, Asthenohymenidae) form a single phylogenetic line, all having the ability to fold their wings over the abdomen when at rest;⁶ and that the other families, such as the Carboniferous Aspidothoracidae, Corydaloididae, Mischopteridae and the Permian Protohymenidae, belong to another phylogenetic line, all holding the wings outspread at rest. This concept separates the family Asthenohymenidae from the Protohymenidae, and indicates that both of these families are highly specialized members of widely divergent lines. The only other alternative is to assume that the Asthenohymenidae have independently developed the neopterous wing folding, the convergent R and CuA, and the other characteristics common to the Elmoid group. Such an assumption seems most unlikely, at best.

⁶ It is of course possible that some other described families, represented only by fragmentary specimens, are members of this series.

We are now confronted by even broader questions than were proposed by Tillyard. First, can these two divergent lines be considered members of the one order, Megasecoptera? Second, is the asthenohymenid line derived from the neopterous stock which produced all other neopterous insects, or does it represent an independent development of folded wings? At present we do not have nearly enough evidence to enable us to answer these questions, but there are certain points which can be brought out at this time. Although the nature of the wing venation and articulation suggests that the Asthenohymenidae and Protohymenidae are not so closely related as Tillyard supposed, both families, and the lines they represent, do possess certain characteristics in common. The wing membrane was smooth and glassy, and the fore and hind wings were nearly homonomous. Both the Asthenohymenidae and Protohymenidae, as well as all other Megasecoptera in which such structural details are known, had very long and multisegmented cerci. The inclusion of the asthenohymenid and protohymenid lines within one order has, therefore, some evidence to support it, in spite of other evidence against it.

The answer to the first question will largely be determined by the answer to the second. If it can be shown that the ability to fold the wings over the abdomen was independently developed in the asthenohymenid line, then presumably there could be no objection to including both lines in the one order. On the other hand, if it can be shown that all or any other orders of neopterous insects have been derived from the asthenohymenid line, the two lines should probably be separated into different orders. The latter possibility has several interesting and significant implications. Tillyard has expressed the conviction (1926) that the Hymenoptera have been descended from his Order Protohymenoptera and specifically from the protohymenid, rather than the asthenohymenid stock. This clearly means an independent development of the neopterous condition in the Hymenoptera and the Asthenohymenidae, for the protohymenid line was obviously palaeopterous. Tillyard has also suggested that the Neuroptera (and presumably all panorpoid orders) were derived from the Megasecoptera (1932), but he does not indicate whether he had reference to the Protohymenidae or some other group of Megasecoptera. This recalls Handlirsch's proposal that the Mecoptera, Trichoptera, Diptera, and Lepidoptera are descended from the Megasecoptera, though he concluded also that the Neuroptera and Megaloptera were independently evolved from the Palaeodictyoptera, and he postulated a polyphyletic origin of

complete metamorphosis. The latest and most radical suggestion is by Forbes (1943), who contends that all the Megasecoptera, including Protohymenidae, had complete metamorphosis and that the genus *Diaphanoptera* was really a primitive genus of Neuroptera.

I have discussed these phylogenetic questions to show the full significance of some of the suggestions which have been made regarding the relationships of the Megasecoptera. In my opinion, far too little evidence is available to enable us to come to any conclusions on these issues. Furthermore, I consider it futile to make taxonomic changes, such as transferring the genus *Diaphanoptera* to the Neuroptera, until the evidence is more nearly conclusive. It is, of course, highly profitable to consider the possible phylogenetic position and significance of fossil and Recent forms, but to change the systematic position of the genera and families according to the latest piece of evidence serves only to increase confusion.

I do propose, however, a modification of the use of the terms "Protohymenoptera" and "Eumegasecoptera." The former was originally employed by Tillyard as an ordinal name to include the Protohymenidae and Asthenohymenidae; but in more recent years it has been used to include all the Megasecoptera-like forms from Permian strata. "Eumegasecoptera" has been employed as a subordinal name for all Carboniferous Megasecoptera. The separation of the families Asthenohymenidae and Protohymenidae into distinct phylogenetic lines, as suggested above, requires a slight change in the concept of the term Protohymenoptera. Since Tillyard specifically stated that the Protohymenidae were the typical members of the Protohymenoptera, they should presumably be included under the latter; and I propose to place also under the Suborder Protohymenoptera the other families of the protohymenid line mentioned above, i. e., the Aspidothoracidae, Corydaloididae, and Mischopteridae. Similarly, I propose that the members of the Asthenohymenid line (*Diaphanopteridae*, *Prochoropteridae*, *Elmoidae*, *Martynovidae*, and *Asthenohymenidae*) be placed in the Suborder Eumegasecoptera. The position of other megasecopterous families, both Carboniferous and Permian, will not be clear until more of their structure is known.

Order PROTODONATA

Seventeen specimens of three species of Protodonata are included in the Midco Collection. These figures indicate that members of the order are relatively less common in the Midco than in the Elmo beds, which has yielded thirty-six specimens of six

species. However, the larger size of the entire collection from Elmo is at least partially responsible for the discrepancy in the figures.

The three protodonates from the Midco beds belong to the family Meganeuridae, each to a different subfamily. All the Elmo species are likewise Meganeurids,⁷ but whereas most of the specimens from Midco are Meganeurines, the majority of those from Elmo are Typines.

Family MEGANEURIDAE

Subfamily MEGANEURINAE

Genus *Meganeuropsis* Carp.

Meganeuropsis Carpenter, 1939, Proc. Amer. Acad. Arts Sci. 73: 39.

This genus was established for a single species (*permiana*) from the Lower Permian of Kansas (Elmo). The species was represented only by two wing fragments of different individuals, but enough was preserved to indicate that the insect was allied to *Meganeura* and that it was at least as large as the Carboniferous *M. monyi* Brong., from France. In the Midco collection there are thirteen specimens of *Meganeuropsis*, all apparently belonging to one species, described below as *americana*. These additional specimens enable us to form a more satisfactory conception of the genus than previously. In the fore wing, the precostal space is long and tapering, extending beyond the middle of the wing, as in all Meganeuridae. Sc continues very nearly, if not entirely, to the apex of the wing. The stems of R and M are partially fused, forming a double vein, as in other Meganeuridae. Rs arises nearly at the separation of R and MA, at a point slightly along MA. R4 + 5 originates about one-fourth the wing length from the base. At the origin of R2 there is a distinct oblique vein, as in the Typinae. One or two cross-veins between 1A and CuP near the base of the wing are slightly oblique, as in *Meganeura*. The area between 1A and the posterior margin is like that of *Meganeura* though the coriaceous area at the very base is not so extensive. The hind wing is unknown, except for a very small piece at the base, showing a strongly curved CuP, as in *Megatypus*.

Meganeuropsis differs from *Meganeura* in having a narrower precostal area basally and a smaller coriaceous area at the base of the anal region. Other differences will probably be apparent when the complete fore wing of *Meganeura* is known. The oblique

vein at the origin of R2 has not been seen in any species of *Meganeura*.

The two known species of *Meganeuropsis* were very large; the new Midco species was about the size of *Meganeura monyi* Brongn. (Commentry, France) while the genotype (*permiana*) was even larger. There is no doubt that *Meganeuropsis* is closer to *Meganeura* than to *Megatypus* and its relatives; but the differences between the Meganeurinae and Typinae are not so great as has been thought. Tillyard (1924, 1925) separated the two subfamilies on the position of origin of R4 + 5 (R3, Tillyard's notation), but the origin of this vein is actually identical in *Meganeura* and *Megatypus* (Carpenter, 1943). The only obvious difference between the two subfamilies is in the length of the precostal area.

Meganeuropsis americana, n. sp.

Figures 22, 23; plate 1, figure 2.

Fore wing: length, as preserved, 280 mm.; estimated entire length, 305 mm. Maximum width, 50 mm. The wing is slender, especially basally. Details of venation are shown in figure 22. Specific characteristics are difficult to select, but probably in this category are the point of origin of R2 + 3 (just proximal of first posterior veinlet of MA), the position of the origin of R2, and the general nature of all branches.

Holotype: No. 4805ab, Museum of Comparative Zoology (loc. 15-L), a very well preserved fore wing, 260 mm. long and 50 mm. wide; it lacks only the apex and a piece along the posterior border. Paratypes: No. 4812ab (loc. 12-M), consisting of a distal piece of a fore wing, from the origin of R2 + 3 to the apex, 115 mm. long. No. 4806ab (loc. 15-L), a piece of the middle of a fore wing, 95 mm. long and 35 mm. wide. No. 4807ab (loc. 15-L), an apical part of a fore wing, 105 mm. long and 45 mm. wide. In addition there are eleven fragments (not designated types), nos. 4808-4811, 4813-4818, from localities 15-L, 8-M, 12-M. Only one appears to be a hind wing; it consists of a piece of a wing base from Sc to 1A, 45 mm. long with CuP very strongly arched as in the hind wings of other Meganeurids. All specimens were collected in the Midco insect beds, Noble County, Oklahoma, by F. M. Carpenter and G. O. Raasch.

This species is undoubtedly closely related to the genotype (*permiana*), which is, however, known only from two fragments, one being the proximal part of a hind wing. Since the cells are larger and the veins thicker in the fragments of *permiana* than they are in *americana*, the former was probably the larger

⁷ The family Calvertiellidae, known only from Elmo, is now placed in the Palaeodictyoptera. See Carpenter, 1943, pp. 536, 548.

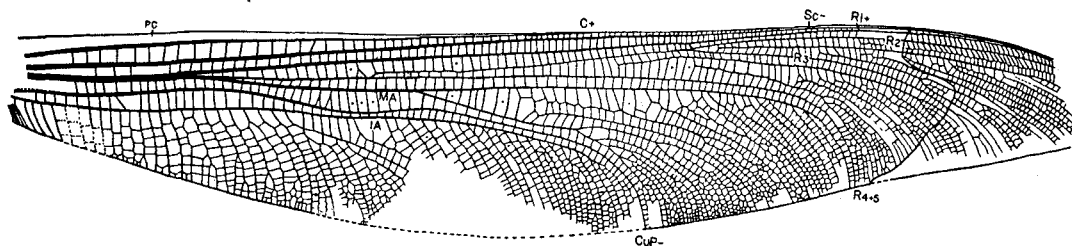


FIGURE 22. *Meganeuropsis americana*, n. sp. Drawing of fore wing, based on holotype and paratypes 4812, 4807. R2, R3 and R4+5, branches of Rs; pc, precostal space; other lettering as in figure 1.

insect. More specimens of *permanian* may indicate that *americana* is identical with it, but until that is certain, I believe the two should be considered distinct.

The holotype wing of *americana*, which is 260 mm. long, is, so far as I am aware, the largest continuous specimen of a wing known. All specimens of *Meganeura monyi*, which had about the same wing expanse as *americana*, consist of smaller fragments. Two of the paratype specimens of *americana* (nos. 4812, 4807) show about 40 mm. more of the distal part of the wing than is preserved in the holotype; since the overlapping areas of these two fossils and of the holotype agree remarkably well, I have added the distal part of these paratypes to the holotype in the drawing of *americana*, figure 22. This brings the length of the part of the wing actually preserved to 300 mm., which is about 5 mm. less than the estimated length of the complete wing.

There are three aspects of *americana* which deserve further comment. One of these is the presence of an oblique vein above the point of separation of R2 and R3. This is obviously the homologue of the vein *Sn* which Sellards described in *Typus permianus* and which also occurs in *Megatypus schrucherti* (Carpenter, 1939). We do not yet know that such a vein existed in *Meganeura*, since the area concerned is not well preserved in any specimen, but I presume it did.

The phylogenetic significance of this vein is not clear, though it is probably homologous with *Sn* of the Odonata.

Another interesting feature of the venation is the thickening of *Sc* near the point of contact with R1 (Figure 23B). Although only 10 mm. long, it is nevertheless distinct and appears to be an incipient pterostigma, not unlike that of some Megasecoptera (e. g. *Prothymenoptera*). No such structure has previously been observed in the Protodonata.

The third noteworthy feature is the presence of plate-like thickenings on the membrane of the wing near the middle of several cells. Their distribution over the wing is indicated in the drawing (Figure 22). Eighteen are clearly discernible in the holotype, and others, not distinct enough for recognition, may also be present. In one of the paratypes (no. 4806) there are a few more platelets than in the holotype, although their general arrangement is the same; and in specimen no. 4817, which is part of a hind wing, there are two between 1A and CuP near the base. Under high magnification they appear to consist of a minute central disc within a larger, less thickened one, about .5 mm. in diameter. Identical structures have been described by Bolton on the wings of the meganeurid *Boltonites radstockensis* (Bolton) from the British Coal Measures, and a few are discernible in the published photograph of this insect (1914, pl.

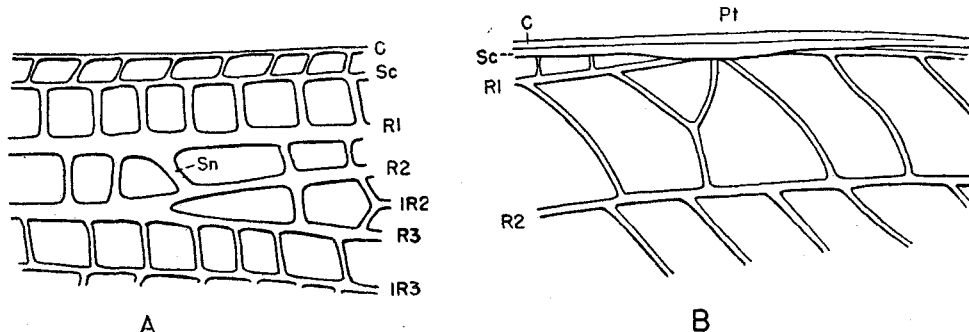


FIGURE 23. *Meganeuropsis americana*, n. sp. A. Drawing of venation in the region of separation of R2 and R3 (holotype). IR2, IR3, intercalary veins; for explanation of *Sn*, see text. B. Drawing of venation near end of *Sc* (holotype). Pt, incipient "pterostigma".

18, fig. 1). Reis has described similar markings on the wings of *Reisia gelasii* (Reis), a possible Protodonatan from the Jurassic of Germany. To my knowledge, these are the only recorded occurrences of such platelets on odonatoid wings. However, since noting them in *Meganeuropsis*, I have looked for similar structures, under relatively high power, on Protodonatan wings from the Elmo beds, in Kansas. They are very distinct in the specimen of *Megatypus schucherti* which I figured in 1943 (Plate 1, fig. 1)—17 between 1A and CuP and a few others in the anal area. None are discernible in specimens of *Typus* or *Oligotypus*. The precise nature of these structures is not at all clear. They may be setal bases, though in that case we should expect to find at least a few of the setae preserved.⁸ Handlirsch has compared those of *Reisia* with similar structures in the Protorthopterous genus *Carcugus* (1911). The latter, however, seem more like the nygmata of various Recent holometabolous insects (see Navas, 1917; Forbes, 1924; Brues, 1933).

Subfamily TYPINAE

Genus *Typus* Sell.

This genus is represented by two species from the Elmo beds in Kansas, and two from the Permian of Arizona. In the Midco collection there is another very distinct species.

Typus gracilis, n. sp.

Figure 24; plate 1, figure 1.

Fore wing: length, 145 mm.; greatest width, 26 mm.; slender. Costal margin straight, apex narrowly rounded, posterior margin with maximum width at level of first fork of MA. The distal half of the posterior margin has a slight arcuate curvature. Only part of the precostal area is preserved; it is similar to that of *permanus*. Sc approaches close to the costal margin at about the level of the origin of R3, but it remains independent of the costa until near the apex of the wing; R1, Rs, and MA arise as in all Typinae; first fork of Rs as in *permanus*, although R2 + 3 and R4 + 5 diverge more gradually; R2 and R3 separate at about two-thirds the wing length from the base; oblique vein (Sn) present as in other Typinae. R2 diverges away from R1 a short distance before the apex of the wing, and IR2 simi-

larly diverges away from R2. Branches of MA more extensive than in *permanus*. The "vestigial CuA" is present as in *permanus*, except that it appears to fork basally. Two slightly oblique cross-veins are present between 1A and CuP near the wing base. Distance between the base of 1A and posterior margin somewhat greater than in *permanus*, and the veins traversing this area are not joined by cross-veins. The cross-veins in the wing as a whole are about as numerous as those in *permanus*, much fewer than in *readi*. Hind wing unknown.

Holotype: no. 4818, Museum of Comparative Zoology; collected in Midco insect beds (loc. 12-M), Noble Co., Oklahoma, by G. O. Raasch. This specimen consists of a complete and well preserved fore wing (plate 1), and is one of the most striking fossils in the Midco collection.

This species presumably had a wing expanse of about 300 mm., nearly one and a half times that of *permanus*. It also differs from *permanus* in having a more slender wing and straighter veinlets between 1A and the posterior margin proximally. It differs from *T. readi* in wing shape and especially in having fewer cross-veins (Carpenter, 1939, fig. 7).

One of the most interesting features of this wing is the structure of the "vestigial CuA" at the base of the wing. This vein apparently occurs in all Typinae (and even in Meganeurinae; see Carpenter, 1943, fig. 2), but it is more clearly preserved here than in other specimens of the group which I have seen. It is composed of two thin veins, one just below M and abruptly curved posteriorly, and the other near the base of CuP and straight. Since both MP and CuA are missing in the Typinae (as well as Meganeurinae), it may well be that the anterior element is a vestige of MP and the posterior one a vestige of CuA. At present, however, there is no Protodonatan known in which these veins are intermediate between the fully developed and vestigial conditions.

Oligotypinae, new subfamily

This subfamily is established for the genus *Oligotypus*, previously known by the genotype specimen from the Elmo beds, and placed in the subfamily Typinae. A new specimen of this insect in the Midco collection provides further information which convinces me that the genus should be separated from *Typus* and *Megatypus* at least by subfamily rank. The characteristics of *Oligotypus* for which the subfamily is formed are as follows: in the fore wing, R2 + 3 and R4 + 5 are widely divergent; Sc terminates slightly beyond mid-wing; MA lacks true branches, so that the area occupied by MA distally

⁸ Dr. W. T. M. Forbes has called my attention to the occurrence of setae on the wing pads of certain odonate nymphs. It is conceivable that in the Protodonata setal bases might have been carried over from the nymphs to the adults.

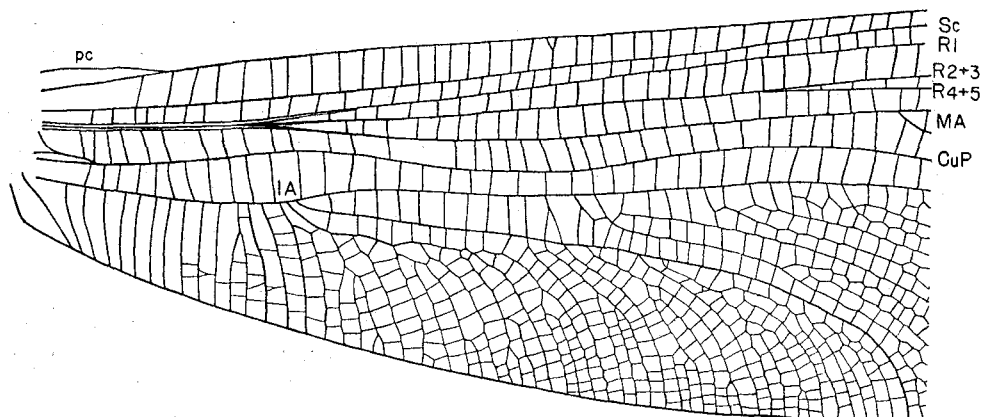


FIGURE 24. *Typus gracilis*, n. sp. Drawing of proximal half of fore wing (holotype). Lettering as in figures 1 and 22.

is very small. The so-called vestigial CuA is completely absent, as is also the oblique vein at separation of R2 and R3. The other two subfamilies of the Meganeuridae (i. e. Meganeurinae and Typinae) are alike in having closely approximate branches of Rs, a longer Sc, a multi-branched MA, and a strong oblique vein at the separation of R2 + R3. *Oligotypus* obviously differs from the Meganeurinae and Typinae more than the latter do from each other. The hind wing of *Oligotypus* is still unknown.

Genus *Oligotypus* Carp.

Oligotypus tillyardi Carp.

Figure 25

Oligotypus tillyardi Carpenter, 1931, Amer. Journ. Sci. 21: 106.

The specimen (no 4804ab, loc. 15-L) in the Midco collection is a fore wing, and, though lacking the distal quarter, is much better preserved in other respects than the holotype. It is the same size as the holotype (40 mm. long, as preserved, 11 mm. wide) and has a very similar venation; but it includes the proximal part of the wing, which, although I was not aware of it, was absent in the type. The base

of the wing is now seen to be essentially like that of other Meganeurids. The precostal area is small, as in *Typus*, and the wing is decidedly narrow across the base. The most interesting aspect of this part of the wing is the total absence of the so-called vestigial CuA, which is apparently present in all other genera of Meganeuridae. The proximal part of the wing is so very well preserved that I am convinced that its absence is not merely due to lack of preservation.

It should be noted that there is no sign in the new specimen of the "obsolescent MP," which I mentioned and figured in my account of the type of *tillyardi*. Further examination of the type convinces me that the short vein indicated in my drawing (1931, p. 107, fig. 2) is really the stem of M, broken away (by pressure) from the stem of R, with which it is normally contiguous.

Order Odonata

Suborder Protozygoptera

Family Kennedyidae

This family is represented in the Midco collection

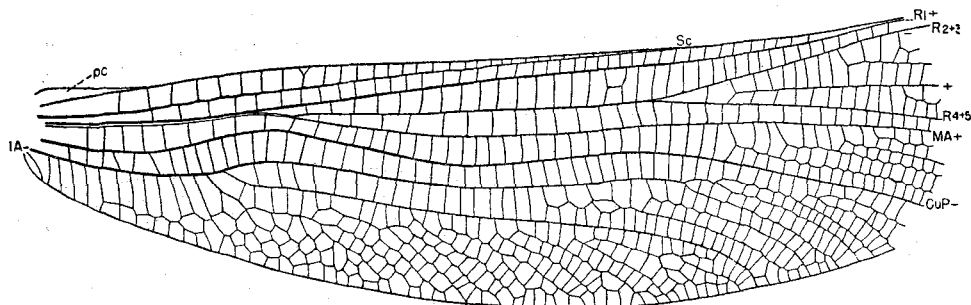


FIGURE 25. *Oligotypus tillyardi* Carp. Drawing of specimen 4804ab, Midco Insect Bed, Noble Co., Oklahoma. Lettering as in figures 1 and 22.

by fifteen specimens, four more than have been secured in the Elmo beds (Kansas). The new fossils belong to the Elmo genera *Progoneura* and *Kennedyia*, but include three new species, two of which greatly extend our knowledge of *Progoneura*. The family Kennedyidae has so far been found only in the Wellington formation. The obscure genus *Sushkinia* from the Russian Permian, though originally assigned to this family by Martynov (1930), has subsequently been placed in the family Permolestidae (Martynov, 1937).

Genus *Kennedyia* Till.

Kennedyia Tillyard, 1925, Amer. Journ. Sci. **10**: 63.

Carpenter, 1939, Proc. Amer. Acad. Arts Sci. **73**: 45.

This genus has previously been known by three species from the Elmo beds: *mirabilis* Till., *tillyardi* Carp. and *reducta* Carp., though the last will probably turn out to belong to another genus. In the Midco collection there is one new species, as well as *mirabilis*. The wings of *Kennedyia* are decidedly petiolate and have a distinct nodal bend on the anterior margin; 1A is long, extending well beyond the level of the nodus. Fraser has pointed out (1939) that in this genus the antenodals are aligned with the subcostal cross-veins below, though this is not always strictly the case, as shown by my figures of *mirabilis* and *tillyardi* (1939, p. 46) and in the figures included here. It is true, however, that they are more nearly aligned in *Kennedyia* than in *Progoneura*.

In the present collection there are nine specimens of *Kennedyia*, of which five are too incomplete for specific determination.

Kennedyia fraseri, n. sp.

Figure 26

Wing: length, 40 mm.; width, 5.8 mm. (holotype); shape much as in *mirabilis*; only three postnodals; pterostigma slightly longer than that of *mirabilis*; 1A close to posterior margin; cross-veins much more numerous distally than in either *mirabilis* or *tillyardi*, forming a distinct reticulation; four cross-veins between R2 and 1R2; five between R3 and 1R2; six

between R3 and 1R3; nine between R3 and R4 + 5. Venation similar to that of *mirabilis* in other respects.

Holotype: no. 4793, Museum of Comparative Zoology; collected in Midco insect beds (loc. 3-M), Noble Co., Oklahoma (F. M. Carpenter and G. O. Raasch). This specimen consists of a complete and well preserved wing. It is probably a fore wing.

Paratypes: no. 4790ab, Museum of Comparative Zoology; same collecting data as holotype, but locality 16. This well preserved wing is 34 mm. long and 5.8 mm. wide; it is a little shorter and relatively broader than the holotype and is therefore almost certainly a hind wing. No. 4821ab, also from locality 16; a nearly complete wing, lacking about 4 mm. of the apex. It has the same dimensions as the previous specimen.

This species is named for Dr. F. C. Fraser, who has greatly advanced our knowledge of Odonate evolution. It differs from the previously described species of *Kennedyia* mainly by having more cells in the distal part of the wing. Of particular interest is the presence of four cross-veins between R2 and 1R2; in *mirabilis* there are no cross-veins at all in this area, and in *tillyardi* (so far as known) there is only one. The large number of cells in *fraseri* carries a suggestion of the condition in Permolestidae.

Kennedyia mirabilis Till.

Kennedyia mirabilis Tillyard, 1925, Amer. Journ. Sci. **10**: 66; Carpenter, 1939, Proc. Amer. Acad. Arts Sci. **73**: 45.

Two specimens apparently belonging to this species are in the Midco collection (no. 4795, loc. 8-M; no. 4798, loc. 5). Each consists only of the distal half of a wing, so that determination is not certain.

Genus *Progoneura* Carp.

Progoneura Carpenter, 1931, Amer. Journ. Sci. **21**: 120. 1933, Proc. Amer. Acad. Arts Sci. **68**: 418. 1939, *ibid.* **73**: 47.

This genus has previously been known only by three specimens of one species (*minuta*) from the Wellington formation in Kansas. Since all of these

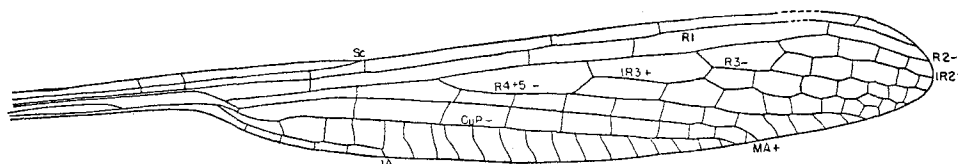


FIGURE 26. *Kennedyia fraseri*, n. sp. Drawing of holotype. R2, R3 and R4 + 5, branches of Rs; IR2 and IR3, intercalary branches of Rs; other lettering as in figure 1.

are fragmentary or poorly preserved, little has been known of the wing venation, except the arculus region and the petiole. In the Midco collection there are five specimens of *Progoneura*, all but one being well preserved and nearly complete wings. It is now possible, therefore, to make a satisfactory comparison of its venation with that of *Kennedya*.

The wings as a whole, though shaped like those of *Kennedya*, are not so abruptly petiolate, the proximal half being more tapering. Also, the costal margin is very nearly straight with hardly a discernible break at the nodus. Two or three antenodals are present,⁹ not aligned with the subcostal cross-veins below; R1 is very remote from Rs. The stem of the arculus is apparently variable in length; in the genotype it is long but in one of the new species (*venula*) it is very short. CuP + 1A is strongly arched below the stem of arculus, and is more undulated in the petiole than it is in *Kennedya*. 1A is very short, ending at least at the level of the nodus. Finally, there are only about half as many cross-veins in *Progoneura* as in *Kennedya*, the venation consequently being very open.

In many respects the genus *Progoneura* is more generalized than other known Protozygoptera. This is indicated by the absence of a nodal bend at the end of Sc, the deviation of the antenodals and the subcostal cross-veins, the tapered petiole, and the undulated CuP + 1A in the petiole. The short 1A and the very small number of cross-veins may also be in this category.

The following species of *Progoneura* are present in the Midco collection.

***Progoneura nobilis*, n. sp.**

Figure 27

Wing: length, 13 mm.; width, 2.5 mm. (holotype). Costal margin with a very slight nodal bend; pterostigma prominent, light reddish brown (as preserved), and slightly swollen; apex pointed; posterior margin conspicuously curved; stem of arculus

⁹ The holotype of *Progoneura minuta* (genotype) has a third antenodal between C and Sc just above the arculus, but there is no indication of this in other specimens.

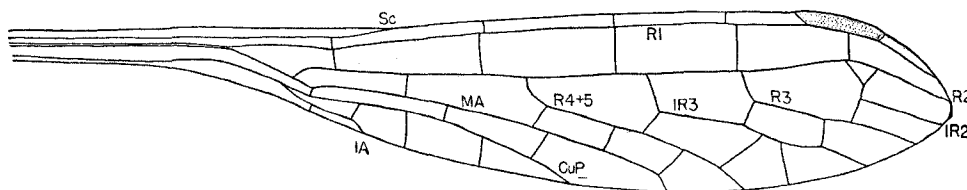


FIGURE 27. *Progoneura nobilis*, n. sp. Drawing of holotype. Lettering as in figures 1 and 26.

long, 1A terminating below the nodus; R4 + 5 arising at a point far distal to level of nodus; cross-veins arranged as in figure 27. The antenodals and "vestigial CuA" are not preserved, the areas including these structures being broken away.

Holotype: No. 4786ab, Museum of Comparative Zoology, collected in Midco insect beds (loc. 16), Noble Co., Oklahoma (F. M. Carpenter and G. O. Raasch). It consists of a complete and well preserved wing.

Paratype: no. 4788ab, Museum of Comparative Zoology, collecting data as for holotype, except for the locality, which is 15-L. This is a nearly complete wing, 15 mm. long and 2.8 mm. wide, lacking only a small piece at the end of MP and at the origin of 1R2. The antenodals are not preserved. The wing is slightly broader at the level of the arculus than it is in the holotype, but the venation is very nearly identical with that of the latter. In all probability the holotype is a fore wing and the paratype a hind wing.

This species is similar in venation to the genotype (*minuta*) but differs in having a much longer arculus stem and in having 1A terminate at about the level of the nodus. Other differences probably exist but further comparison cannot be made because of our incomplete knowledge of *minuta*.

***Progoneura venula*, n. sp.**

Figure 28

Wing: length (as preserved), 16 mm.; width, 2.8 mm.; estimated whole length, 17.5 mm. Costal margin without a discernible nodal bend, pterostigma prominent, somewhat longer than that of *nobilis*; apex pointed; posterior margin not so strongly curved as in the latter; stem of arculus very short, much like that in *Kennedya*, 1A terminating far proximal to the level of the nodus; two antenodals present; the more distal antenodal occurring in *minuta* is not visible in *venula*, possibly because the membrane is partially broken away at the corresponding region. Cross-veins arranged as shown in figure 28.

Holotype: No. 4791, Museum of Comparative Zoology; collected in Midco insect beds (loc. 16-M),

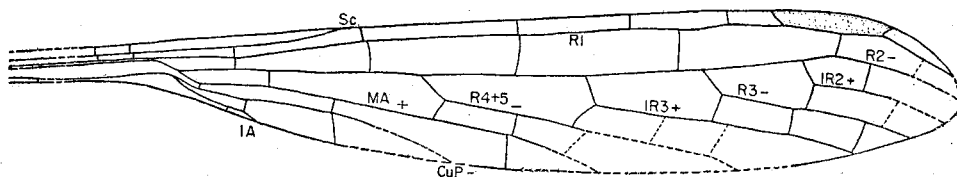


FIGURE 28. *Progoneura venula*, n. sp. Drawing of holotype. Lettering as in figures 1 and 26.

Noble Co., Oklahoma (F. M. Carpenter and G. O. Raasch). The specimen consists of a nearly complete and well preserved wing, lacking the very base of the petiole and a small piece along the posterior margin.

This wing differs from those of *nobilis* and *minuta* in having a very short arculus stem, with the corresponding shift in the position of A1; and in having the origin of R4 + 5 more proximal.

Progoneura sp.

In addition to the above, the Midco collection contains one specimen (no. 4792, loc. 8-M), which apparently represents a third species. It consists of the proximal half of a wing, 17 mm. long, indicating that the whole wing was about 34 mm., fully twice the size of other species of the genus. The preserved part of the wing is characteristic of *Progoneura*, but since the nodus and the distal piece of Sc are not known, I believe the species should not be described until more specimens have been found.

Suborder PROTANISOPTERA

Family DITAXINEURIDAE

Ditaxineura cellulosa Carp.

Ditaxineura cellulosa Carpenter, 1933, Proc. Amer. Acad. Arts Sci. 68: 419.

This species is represented in the Midco collection by the distal fragment of a wing (no. 4801ab, loc. 8-M), 14 mm. long. Its size, venation and pterostigma agree fully with those of *cellulosa*, described from the Elmo beds. The convexities and concavities are very well preserved and show that the posterior "branch" of MA depicted in my figure of *cellulosa* (1933) is really a concave, intercalated sector, as in *anamalostigna*. In the type of *cellulosa* the concavity of the vein was obscured by irregularities.

A second wing fragment (no. 4802ab, loc. 15-L) also belongs to *Ditaxineura*, probably to *cellulosa*, but it consists of the proximal half of the wing only, and is poorly preserved, so that its specific identity is uncertain.

REFERENCES

- BOLTON, H.
1914. On the occurrence of a giant dragon-fly in the Radstock Coal Measures. Quart. Journ. Geol. Soc., 70: 119-126.
- BRONGNIART, C.
1885. Les insectes fossiles des terrains primaires. Bull. Soc. Amis. Sci. Nat. Rouen, 1885: 50-68.
1894. Recherches pour servir à l'histoire des insectes fossiles des temps primaires. Bull. Soc. Industr. Minérale, 7 (4): 124-615.
- BRUES, C. T.
1933. A new genus of Phoridae from Peru. Psyche, 40 (3): 106-111.
- CARPENTER, F. M.
1931a. The Lower Permian insects of Kansas. Part 2. The Orders Palaeodictyoptera, Protodonata and Odonata. Amer. Journ. Sci. (5) 21: 97-139.
1931b. Same, Part 3. The Protahymenoptera. Psyche, 37: 343-374.
1933. Same, Part 6. Delopteridae, Protelytroptera, Plectoptera, and a new collection of Protodonata and Psocoptera. Proc. Amer. Acad. Arts Sci., 68: 411-504.
1939. Same, Part 8. Additional Megasecoptera, Protodonata, Odonata, Homoptera, Psocoptera, Protelytroptera, Plectoptera and Protoperlaria. Proc. Amer. Acad. Arts Sci., 73: 29-70.
1943a. Same, Part 9. The Orders Neuroptera, Raphidioidea, Caloneuroidea and Protorthoptera (Probnisidae), with additional Protodonata and Megasecoptera. Proc. Amer. Acad. Arts Sci., 75 (2): 55-84.
1943b. Studies on Carboniferous insects from Commeny, France; Part I. Introduction and families Protagriidae, Meganeuridae, and Campylopteridae. Bull. Geol. Soc. Amer., 54: 527-554.
- DUNBAR, C. O.
1924. Kansas Permian insects. Part I. The geologic occurrence and the environment of the insects. Amer. Journ. Sci., (5) 7: 171-209.
- FORBES, W. T. M.
1943. The origin of wings and venational types in

- insects. Amer. Midland Natural., **29** (2): 381-405. TILLYARD, R. J.
- FRASER, F. C.
1939. A reclassification of the Order Odonata. Austr. Zool., **9** (2): 195-221.
- HANDLIRSCH, A.
1906. Die fossilen Insekten. Wien.
1911. New Palaeozoic insects from the vicinity of Mazon Creek, Illinois. Amer. Journ. Sci., (4) **31**: 297-326, 353-377.
- MARTYNOV, A. V.
1930. New Permian insects from Tikhie Gory, Kazan Province. 1. Palaeoptera. Trav. Mus. Geol. Acad. Sci. URSS, **6**: 69-86.
1937. Permian fossil insects from Kargala and their relationships. Trav. Inst. Paleont. Acad. Sci. URSS, **7**: 1-92.
1940. Permian fossil insects from Tshekarda. Trav. Inst. Paleont. Acad. Sci. URSS, **11**: 1-62.
- RAYMOND, P. E.
1944. Late Paleozoic Xiphosurans. Bull. Mus. Comp. Zool., **94** (10): 475-508.
1946. The genera of fossil Conchostraca—An Order of bivalve Crustacea. Bull. Mus. Comp. Zool., **96** (3): 216-307.
- REIS, O. M.
1909. Handlirschia Gelasii n. g. et sp. aus dem Schaumkalk Frankens. Abh. K. Bayr. Akad. Wiss., **23** (3): 661-694.
- SARS, G. O.
1896. Fauna Norvegiæ. Bd. I. Phyllocarida og Phyllopoda. Christiania. Pp. 113-114.
1924. Kansas Permian insects. Part 3. The new Order Protohymenoptera. Amer. Journ. Sci., (5) **8**: 111-122.
1926. Same, Part 6. Addition to the Orders Protohymenoptera and Odonata. Amer. Journ. Sci., (5) **11**: 58-73.
1932. Same, Part 14. The Order Neuroptera. Amer. Journ. Sci., (5) **23**: 1-30.
1936. Same, Part 16. The Order Plecoptera (cont'd): The family Doteridae, with a note on the affinities of the Order Protohymenoptera. Amer. Journ. Sci., (5) **32**: 435-453.
1937. Same, Part 17. The Order Megasecoptera and additions to the Palaeodictyoptera, Odonata, Protoperlaria, Copeognatha, and Neuroptera. Amer. Journ. Sci., (5) **33**: 81-110.
- ZALESKY, G.
1937a. Nouveaux représentants des Protohymenoptères et des Archodonates provenant du terrain Permien du bassin de la rivière Karna et leurs liens de parenté. Ann. Soc. ent. France, **106**: 101-114.
1937b. Études des insectes Permien du bassin de la Sylva et problèmes de l'évolution dans la classe des insectes. Prob. Paleont., **2-3**: 601-607.

Harvard University
Cambridge, Mass.

EXPLANATION OF PLATES

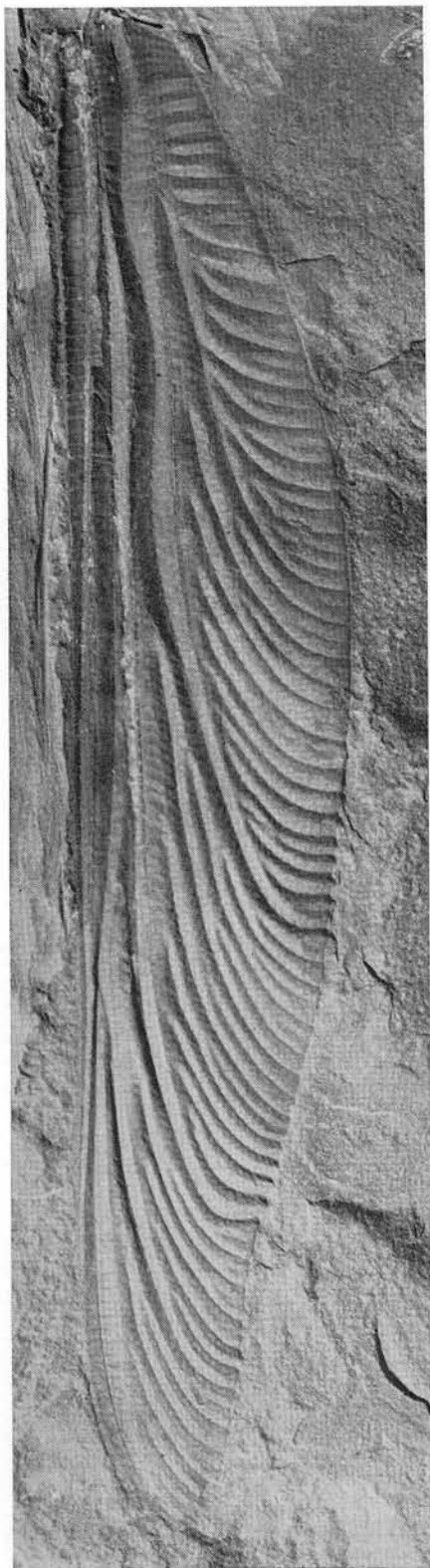
PLATE 1

- FIGURE 1. *Typus gracilis*, n. sp. Photograph of holotype (4818). $\times 1.3$
FIGURE 2. *Meganeuropsis americana*, n. sp. Photograph of holotype (4805). $\times .65$

PLATE 2

- FIGURE 1. *Eumartynovia raaschi*, n. sp. Photograph of holotype (4822). $\times 8.5$
FIGURE 2. *Parelmoa revelata*, n. sp. Photograph of holotype (4680). $\times 12$

PLATE 1

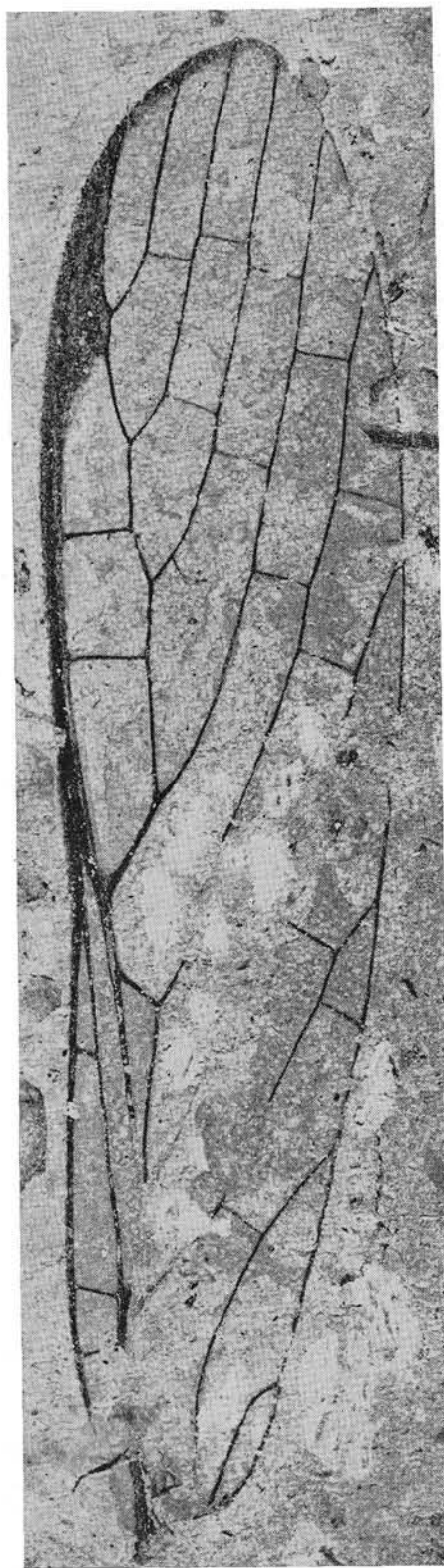


1

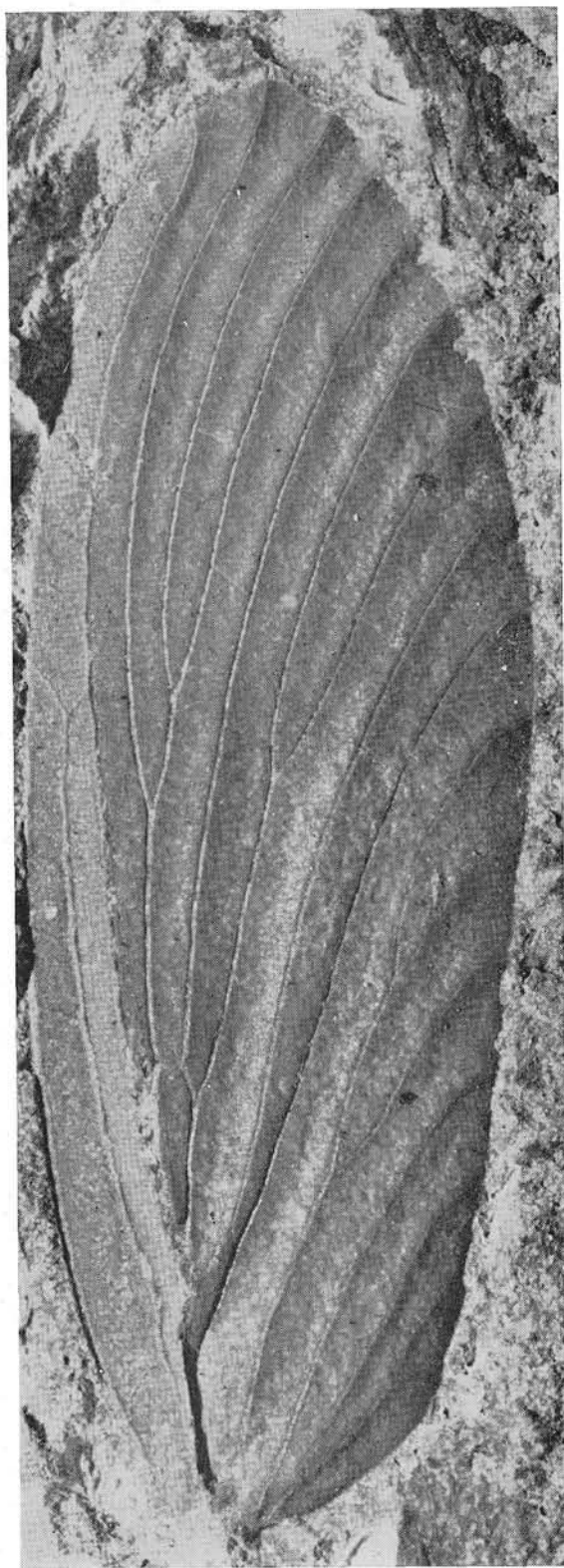


2

PLATE 2



1



2

Proceedings of the American Academy of Arts and Sciences

VOL. 76, No. 3, P. 55-87—MARCH, 1948

THE COMPRESSION OF 39 SUBSTANCES TO 100,000 KG/CM²

By P. W. BRIDGMAN

ROUGH COMPRESSIONS OF 177 SUBSTANCES TO 40,000 KG/CM²

By P. W. BRIDGMAN

INVESTIGATIONS ON LIGHT AND HEAT MADE AND PUBLISHED WITH AID FROM THE
RUMFORD FUND

THE COMPRESSION OF 39 SUBSTANCES TO 100,000 KG/CM²

By P. W. BRIDGMAN

Harvard University, Cambridge, Massachusetts

Presented Oct. 25, 1947.

Received Oct. 25, 1947.

TABLE OF CONTENTS

Introduction.....	55
Apparatus and Method.....	55
Detailed Results.....	60
Alkali Metals.....	60
Other Elements.....	62
Beryllium.....	62
Carbon (graphite).....	62
Magnesium.....	63
Aluminum.....	63
Silicon.....	63
Phosphorus.....	64
Black Phosphorus.....	64
Violet Phosphorus.....	64
Titanium.....	64
Manganese.....	64
Germanium.....	65
Arsenic.....	65
Zirconium.....	65
Lanthanum.....	65
Cerium.....	65
Praseodymium.....	65
Neodymium.....	65
Thorium.....	65
Uranium.....	66
Certain Compounds.....	66
Quartz Crystal and Six Glasses.....	67
Discussion.....	69

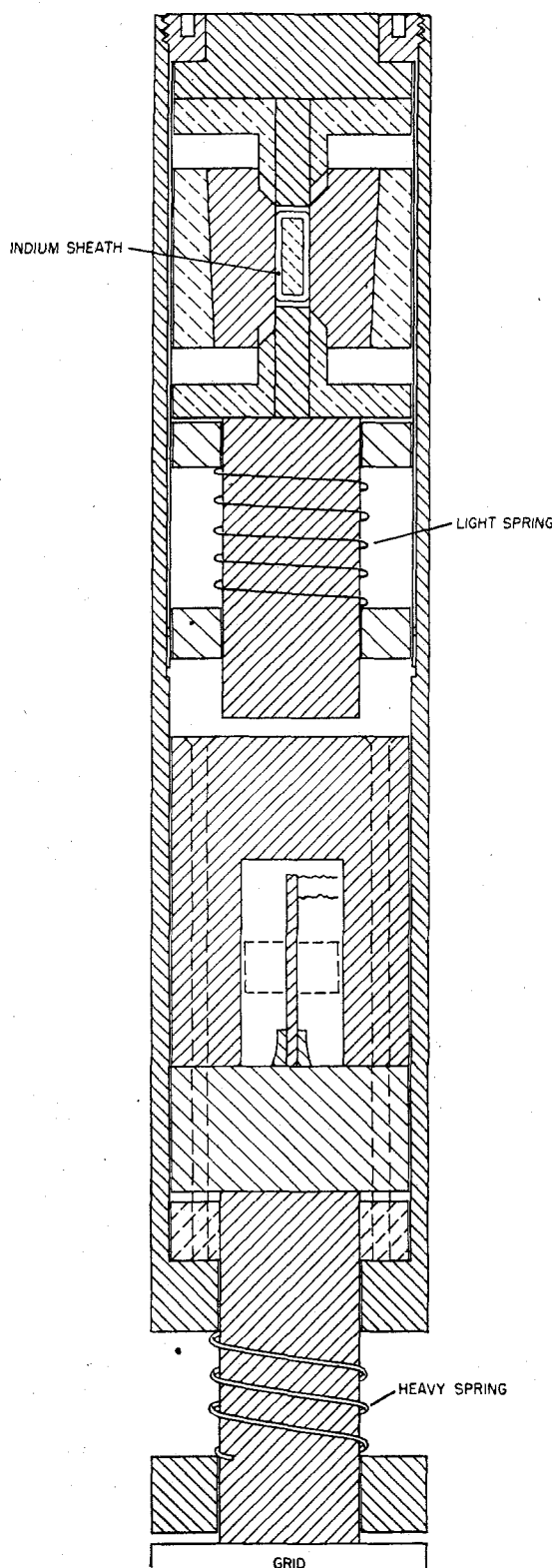
INTRODUCTION

In this paper the program of measurement of the compressions of various substances to 100,000 kg/cm² already initiated in two papers (1) is continued to 39 substances, including elements, various sulfides, selenides and tellurides, and 6 glasses. A number of improvements have been made in the apparatus, permitting somewhat greater accuracy and consequently the extension of the measurements to substances with too low a compressibility to have been previously attempted.

APPARATUS AND METHOD

The apparatus consists essentially of a miniature high pressure piezometer entirely surrounded by an outer pressure vessel containing fluid in

which the pressure may be raised to 30,000 kg/cm² in order to support the miniature piezometer. Measurements are made of the force driving the pistons of the high pressure piezometer and the displacement of those pistons. Previously the force has been measured in terms of the change of electrical resistance of a compression member mounted within the pressure vessel by which the force is transmitted to the high pressure pistons, and the displacement by measuring the displacement of the piston of the external pressure vessel, which is transmitted through various intermediate members to the high pressure pistons. This latter measurement has always been more or less unsatisfactory because of the distortion of the transmitting members, which are subject to friction and hysteresis in a way not completely reproducible. The major improvement in the new apparatus consists in measuring the displacement of the high pressure pistons from the inside of the 30,000 pressure vessel, thus eliminating the irregularities due to friction and hysteresis. This has been done by attaching the pistons to a moving slide wire of the same type as that used in much of my previous work. The displacement of the wire is determined in terms of the potentiometer resistance of that portion of the wire included between a terminal fixed to the wire and a contact fixed to the rest of the apparatus over which the wire slides. The method demands three electrically insulated leads, two for the potential taps to the potentiometer, and one for the current, the other current terminal being grounded. In all, seven electrically insulated leads into the pressure vessel are now needed, three for the "grid" with which the force driving the piston is measured, one for the manganin pressure gauge, and three for the displacement. Formerly, it had not been found possible to make insulating pressure plugs which would carry more than four terminals. My mechanic, Mr. Charles E. Chase, has now found with great skill how to construct plugs with seven terminals, and this alone has made possible the improvement in the method. No essentially new feature is involved



in the new plug, but only the refinements of smaller and more accurate construction. The individual terminals are like those shown in Figure 2. As experience has been gained, it has become possible to dispense with various artifices formerly thought necessary, such as the secondary plastic packing above the cones, and the preliminary application of pressure with a heavy oil. At the same time the life of the insulation has been very much extended; seventy-five applications of 25,000 to 30,000 have been made before it was necessary to renew the insulation, whereas when this work started a single application could not be counted on.

In addition to this major improvement a number of minor improvements were made. The sensitivity of the grid with which the force driving the pistons is measured was doubled by changing the dimensions, making the grid shorter and thinner in section. The sensitiveness of the force measurement is now about one part in 200 at the maximum. This measurement was the mean of three settings on the potentiometer wire, with different directions of current flow and in a time sequence to eliminate effects due to any drift in the parasitics, and could be counted on to the limit of sensitivity of the individual readings, 0.1 mm. on the slide wire, or perhaps a trifle better. The sensitivity of reading of piston displacement was, with the original arrangements, some ten or twenty times as great as this. So great sensitivity could not all be used, and therefore opportunity was taken to improve the design of the piezometer and pistons, at the same time cutting down the displacements to one half. This was done by giving the piezometer the design shown in Figure 1 and in greater detail in Figure 3. The effective occupied length, that is, the length of the charge, is cut to one half by enlarging the mouth of the piezometer at both ends as shown. The stroke of the piston is correspondingly cut in half, which makes it possible to more effectively support the piston and minimize its plastic flow and lateral expansion. The new design of the piezometer decreases the friction of the charge as it slides on the sides of the piezometer by more than a factor of two, friction being exponential in the length, increases the bursting pressure of the piezometer appreciably because of the support afforded by the end regions

FIGURE 1. General view of the assembly, showing how the motion of the pistons of the piezometer (upper part) is transmitted to the measuring wire (lower part).

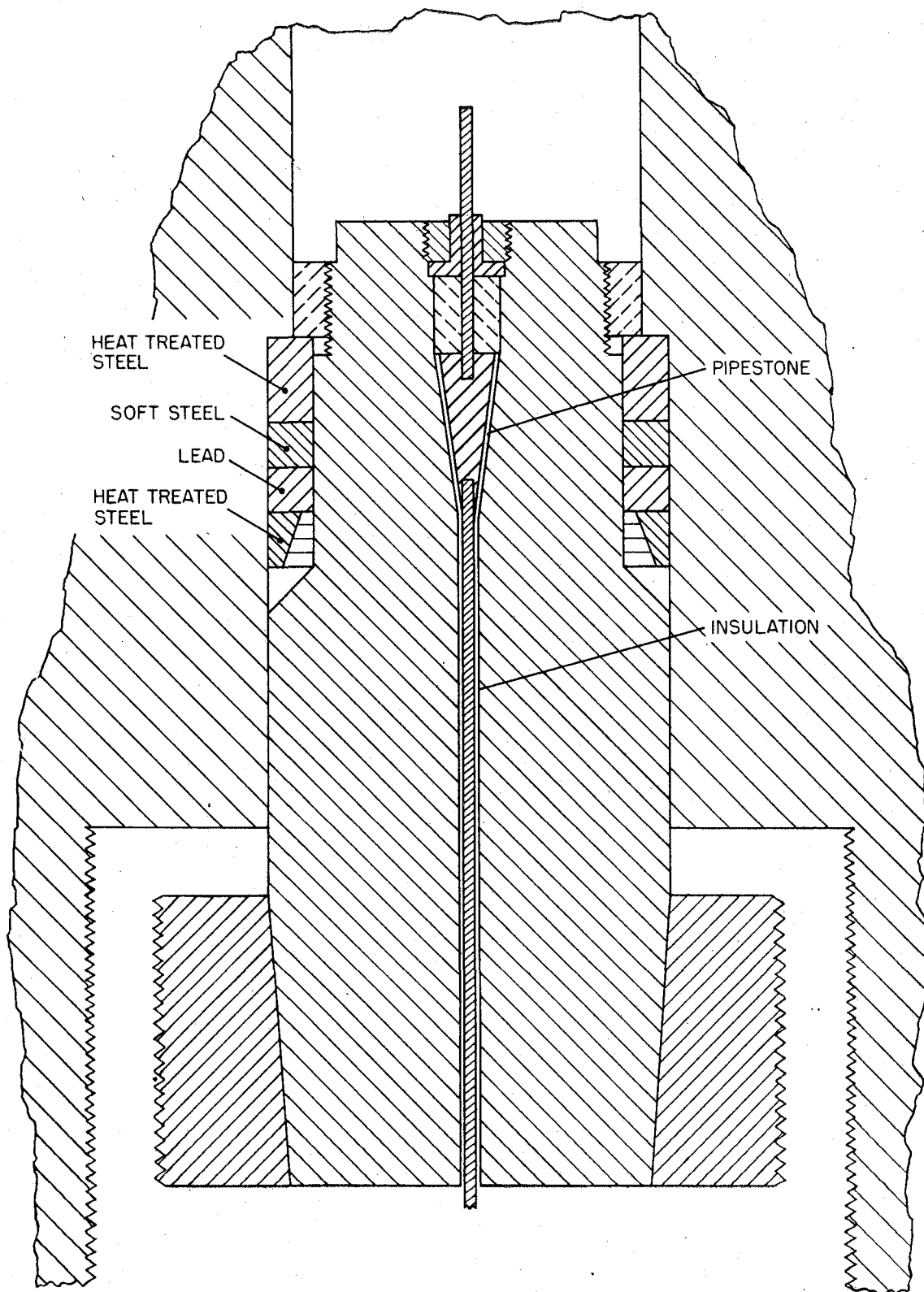


FIGURE 2. Improved design for getting electrical leads into the pressure cylinder, together with the improved split ring packing.

which are not exposed to internal pressure, and by the same mechanism decreases the barreling of the interior under internal pressure and so minimizes a small source of error in the computed distortion of the piezometer. The piezometers were made of grade 799 carboloy, with shrunk on steel jacket. This grade of carboloy has proved exceedingly well adapted for this purpose, no piezometer made of this grade ever having ruptured in use. In my earlier work ruptures of the

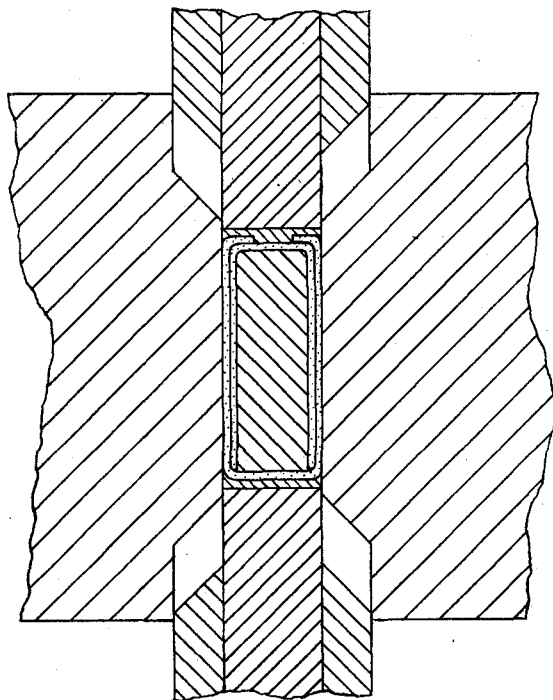


FIGURE 3. Enlarged view of the piezometer, showing method of sealing an alkali metal inside a double capsule of aluminum.

piezometer were common, but the piezometers were then made of the less suitable 905 grade. In the present work one piezometer has been exposed to 40 and the other to 50 applications of the maximum pressure, which was always at least as high as 100,000 and might infrequently reach nearly 110,000. The plastic flow of the piezometers under these conditions was slight. In use there is perceptible plastic enlarging of the interior, but this is very slow. During operation it was necessary to refigure only once by enlarging the bore from 0.0620 to 0.0625 inches. The pistons, as described previously, were best made of grade carboloy 999. The quality of this grade is not entirely uniform and it is desirable

to make preliminary examination to find a batch with a high plastic flow point. In use the pistons are made 0.0004 inches smaller than the hole so that at no time will they expand sufficiently to touch the sides of the cylinder and thereby introduce friction. Under these conditions the pistons permanently expand by about 0.0001 inch after every excursion to the maximum, and they have to be refigured after every such use. Eventually after perhaps a dozen or fifteen refigurings the flow limit is reached, minute cracks begin to appear, and the pistons must be replaced. The shrunk on steel support around the unused part of the piston, as shown in Figure 3, materially adds to the life; there is no plastic flow in this part of the piston. The clearance of 0.0002 inches between piston and cylinder walls is large enough to put demands on the cup shaped steel packing between the end of the piston and the charge. If this is made of a soft steel it will be extruded between piston and wall with consequent friction and also danger of discing off the end face of the piston where it is pinched. A packing made of a heat treated steel with a Rockwell C hardness of 40 gave no trouble from this extrusion.

Friction between charge and cylinder walls was further materially reduced below that attained by halving the length of the charge by completely encasing the charge in an indium sheath. This sheath was formed in place in the cylinder with a suitable forming tool. There is, of course, a disadvantage in that the presence of the indium cuts down the amount of working substance and furthermore introduces an additional correction because of its compression. The advantages, however, usually outweighed the disadvantages. If the substance is mechanically soft, such as aluminum or magnesium, the sheath may be omitted. The volume of the indium in the sheath was usually approximately one half that of the working charge. Quantities of indium and charge were determined by weighing in a specially constructed micro-balance good to better than 0.00001 gm.; the usual weight of the indium was around 0.016 gm.

Two improvements were made in the technique of handling the production of the supporting pressure of 30,000 kg/cm². At one time a long series of capricious irregularities was encountered which was finally traced to freezing of the transmitting liquid, i-pentane. This was commercial material from the Eastman Kodak Company. The trouble was finally associated with the use of a new batch of this liquid. The explanation is

that Eastman has recently improved their method of preparing this liquid, so that it is now purer than formerly and therefore has a sharper freezing point. The remedy is to mix with the i-pentane half its volume of commercial "pentane." Even this mixture at the maximum pressure capriciously becomes sufficiently viscous to introduce appreciable non-hydrostatic forces, so that a redesign of the method of coupling the pistons to the slide wire measuring their displacement was necessary. Originally the coupling was by push contact for one direction of stroke, but on the reverse stroke a stiff spring was used to maintain contact. The spring was not strong enough always to overcome the stiffness of the liquid, so that the connection had to be redesigned to ensure positive transmission of motion for both directions of stroke. The second change in technique was in the packing ring closing the insulating plug at the bottom of the 30,000 apparatus. This had never been entirely satisfactory, but would leak slightly after long use in a way not easy to definitely locate. It appeared that after prolonged use with consequent work hardening the packing ring becomes loose on the inside surface, while remaining tight at the outside. The remedy was to make the packing ring double, an inside part sliding conically in the outer part, as indicated in Figure 2. In virtue of slip on the conical surface the inside as well as the outside now is pressed tightly against the retaining walls. Some fifty applications have been made without leak, the apparatus then having been taken down for another reason.

The various corrections and calibrations necessary in connection with the slide wire method of measuring displacement were determined by methods sufficiently obvious which have been previously used, so that they need not be described again in detail. It is an advantage of the method that the corrections are all small. The pressure coefficient of resistance of the wire was determined by a pressure run with the wire clamped. The validity of the corrections and calibrations was checked by measuring between 25,000 and 30,000 a known displacement of the same magnitude as the piston displacements encountered during the compression measurements. This was done by measuring the plastic shortening of a cylinder of copper, the shortening being terminated by a hardened steel stop when it had progressed by a known amount. The driving force is plotted as a function of displacement. There is a discontinuous change in direction when

contact is first made with the copper and again when the stop is encountered. Since the cubic compressions of steel and copper are known, all the material is at hand for a calculation of the expected displacement, thus permitting a comparison with that given by the slider. The two measurements differed by 0.0001 inch on a displacement of 0.0350 inch, which is agreement to better than the sensitiveness of the force measurements.

The new set-up permits a check of a correction in the measurement of driving force by means of the grid. This correction is for the pressure coefficient of the simple compression coefficient of the electrical resistance of the grid. It is the largest of any of the corrections in this work, rising to something over twenty per cent. It had been previously determined from the average of several hundred determinations of the extra

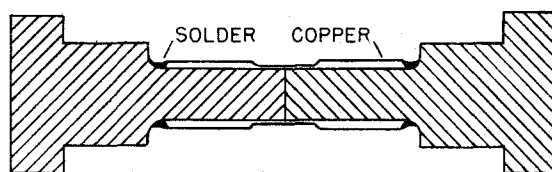


FIGURE 4. The compound tension specimen, with which the correction for the effect of pressure on the compressive constant of the "grid" is determined.

force required to drive the main piston of the 30,000 apparatus when it makes up against the grid. There is a rather large component of friction, and there was much scatter in the individual readings, so that an entirely independent confirmation was desirable. The possibility of such confirmation was afforded by the method used for studying the effect of pressure on the tensile strength of brittle substances described in a previous paper (2). The tension specimen is replaced by a double specimen of hardened steel, as indicated in Figure 4. A thin copper sheath unites the two steel pieces. The specimen was mounted in the holder for tensile specimens in the 30,000 apparatus, and, at a pressure of 21,000, the tensile force is measured which is required to separate the two steel specimens by measuring the change of resistance of the grid. The thin copper sheath prevents entrance of the transmitting liquid between the ends of the steel pieces, so that the force required to separate the steel pieces is equal to the force exerted by the known hydrostatic pressure over the cross section, plus a

small correction, about 2 per cent, for the breaking strength of the copper. The agreement was perfect between the separating force determined from the hydrostatic pressure and that calculated from the resistance change of the grid using the previously determined pressure correction, thus checking the latter.

Having determined the displacements and the force on the piston, the final results are to be computed in exactly the same way as in previous papers, so that this need not be described again. In this computation the fiducial volume is that at 25,000 kg/cm². For many of the substances of this paper an independent determination of this has not been previously made, so that new measurements up to 25,000 were desirable. These were made in a new apparatus permitting very rapid measurements at room temperature with very small corrections. This apparatus has been previously described (3) and results obtained with it for 61 substances up to 25,000 kg/cm². It has now been found that the same apparatus can be used without modification up to 40,000 instead of 25,000 and measurements have been made with it on some 175 new substances, including those of this paper. For these substances we thus have overlapping measurements by two different methods in the range between 25,000 and 40,000, which affords a desirable check. This check, however, is not given under optimum conditions, since the comparison is between the upper end of the range of one instrument and the lower end of the range of the other. In a few cases the fiducial volume at 25,000 was not independently known from other experiments. In these cases it is possible to obtain a fairly satisfactory value from the absolute setting of the potentiometer when the high pressure pistons first establish contact with the grid in the neighborhood of 25,000. It is the differential settings of the potentiometer which determine the volume changes above 25,000.

The final results are, as before, strictly differential results between the substance in question and gold, assuming for the latter an extrapolation by Murnaghan's formula. Even if the accuracy of the measurements permitted it, which they do not, we are not yet in a position to obtain the absolute compressibility of any single one of the relatively incompressible substances up to 100,000 with any accuracy. The relative compressibilities, however, are determinable within the accuracy of the measurements.

In making the measurements, complete data

were recorded for the piston displacement by both the former (external piston) and the new (slide wire) methods. The displacements by both methods were calculated for about half the substances. These definitely established the superiority of the new method, both in smoothness and consistency, while at the same time showing no over-all discrepancy between the two methods, so that there is no reason to fear any consistent error in the results already published. In view of this and also of the fact that calculations by the former method are much more time consuming than by the new, only the new data by the slider method were used in the computations for the other half of the substances.

As before, most of the substances were independently measured in two different piezometers. There are, however, a few of the more incompressible and unusual elements which have been measured in only one piezometer. Since in any event no high accuracy can be expected for these elements the chief interest of the measurements for them lies in the information obtained with regard to the presence or absence of new polymorphic forms in the new pressure range.

The detailed presentation of results now follows. The order is: first the five alkali metals in order of atomic weight, then 17 other elements in order of atomic weight, then ten compounds including the sulfides, selenides and tellurides of zinc, mercury and lead, and quartz crystal, and finally six glasses.

DETAILED RESULTS

Alkali Metals. Results for all of these metals except caesium have already been published. These are of especial theoretical interest because the structure of these elements is sufficiently simple to permit theoretical calculation of the volume changes under pressure. Furthermore, they should at first sight be among the easiest to measure experimentally because the compressibilities are among the highest of the elements. Unfortunately, however, they turn out to be among the most difficult to determine experimentally, and of all the materials formerly measured the results were least accurate for them. It was therefore thought to be worth while to redetermine them with the present more accurate method. The difficulty arises from the great mechanical softness of these metals and their high chemical activity. It had already been established that the carboloy piezometer is ruptured if pressure is directly transmitted to it by sodium,

and there was evidence that lithium might produce a similar fracture. Accordingly the alkali metal has to be enclosed in some sort of a protecting sheath. This sheath should obviously be as soft mechanically as feasible. In the previous work a sheath of copper was used, the total volume of the copper being of the order of twice that of the metal and its contribution to the compressibility of the order of one fifth that of the alkali. The friction exerted by so much copper proved to be sufficient to introduce a rather large uncertainty into the final result. In attacking the problem again, search was first made for a softer metal out of which to make the protecting sheath. Sodium was first tried in a sheath of indium. On application of 100,000 there was a large permanent change of volume, and on release the two metals were found to be completely alloyed. Sodium in a sheath of lead was then tried. Again there was an irreversible and permanent decrease of volume, much less than before, but too much. On cutting open the capsule a region of alloying was found at the surface of contact. It was concluded from this experience that alloying would be produced in the cold by these high pressures if the alloy existed. The extremely extensive book of M. Hansen on binary alloys of the metals was then consulted, and the softest metal known not to alloy with the alkali metals found to be aluminum. This is harder than would be desirable, but still much softer than copper. The aluminum sheath was made in the form of a double cup, as indicated in Figure 3. A simple technique was worked out by which the filling was accomplished under petroleum ether, the petroleum ether removed by evaporation, still leaving a protecting atmosphere of petroleum ether, the outer cup slipped over the filled inner cup, and the projecting edge of the outer cup swaged over the inner cup while still in the protecting atmosphere, and then the final closure of the cup accomplished by spinning in a jeweler's lathe. The atmosphere was thereby effectively excluded, and the capsules were capable of remaining indefinitely in the air of the room with no evidence of chemical action. The quantities were determined by an initial weighing of the aluminum cups and a final weighing of the filled capsule. In the case of caesium the room was cooled to about 10° C by opening the windows during the filling, and all pieces of metal in contact with any part of the filling apparatus as well as the petroleum ether were prechilled to 0° C. Caesium was not previously measured above

45,000. The reason for this was entirely accidental; the apparatus for 100,000 had been filled and pressure applied up to the maximum when the piezometer broke. This was at the end of the previous series of measurements, when war work was pressing to be done, and I was not able at that time to return to it. Except for the inconvenience of the low melting point, there is no greater intrinsic difficulty with caesium than with any of the other alkali metals, and the same arrangements will serve.

The source of the alkalis, except caesium, was my own stock, with which many of my previous results have been obtained and known to be of adequate purity, kept sealed under Nujol. The caesium, however, was obtained from a previously unopened glass capsule sealed in vacuum obtained from Mackay before the war, one of several such capsules, others of which had been used in my previous work. The caesium was obviously impure with its own oxide, as shown by its bright yellow color and indefinite freezing. It was purified, as in my previous work, by distillation at the minimum temperature in a high vacuum and over an interval of several hours. The evidence of purity is the disappearance of the yellow color and sharpness of freezing.

The volumes of the five alkalis obtained with the present apparatus are shown as a function of pressure in Table I. As already mentioned, the

TABLE I
VOLUME OF THE ALKALI METALS

Pressure kg/cm ²	Lith- ium	Sodium	Potas- ium	Rubid- ium	Cae- sium
1	1.000	1.000	1.000	1.000	1.000
25,000	.851	.789	.691	.675	.609
30,000	.833	.770	.668	.652	.571
40,000	.801	.737	.628	.612	.521*
50,000	.773	.708	.595	.578	.431
60,000	.748	.683	.568	.551	.409
70,000	.727	.661	.546	.528	.392
80,000	.707	.641	.528	.507	.381
90,000	.689	.623	.513	.489	.375
100,000	.672	.606	.500	.473	.368

* Discontinuity of volume of .056 at 45,000

volumes at 25,000 kg/cm² are those given by measurements in the new apparatus for 40,000. Values of the volumes below 40,000 will be found in a paper following this describing the results with that apparatus. It is debatable how best to present the final results in the pressure range in which there are independent determinations with different pieces of apparatus. In some of my early work the course was adopted of adjust-

ing the values given by one apparatus in the direction of those given by the other in the overlapping ranges. Such a procedure is obviously to a certain extent arbitrary. The simpler and perhaps safer course is now adopted of reporting the results obtained with the present apparatus for 100,000 without any adjustment at all for the results obtained with the 40,000 or other forms of apparatus. The values obtained with the two pieces of apparatus at 40,000 will be stated however. This will put the reader in a position, in conjunction with the data of the other paper, to make his own adjustments as he sees fit. The same course will be followed with the other materials of this paper. The comparison of the results with the two pieces of apparatus is as follows. At 40,000 the volume obtained with the 40,000 apparatus for lithium was 0.796 against 0.801 with the present 100,000 apparatus; for sodium 0.726 against 0.737; for potassium 0.633 against 0.628; for rubidium 0.605 against 0.612; and for caesium 0.518 against 0.521. The results with the 40,000 apparatus at 40,000 are somewhat lower than with the present apparatus, which means that the 40,000 apparatus gives a somewhat greater compressibility in the range 25,000 to 40,000 than does the present apparatus.

Compared with the previous measurements to 100,000 the new measurements give consistently larger volumes at the top pressure than before. The difference is spread over the entire pressure range, but accelerates markedly at the upper end of the range. The comparison of the volumes at 100,000 is as follows: for lithium 0.672 now against 0.606 before; for sodium 0.606 against 0.560; for potassium 0.500 against 0.427; and for rubidium 0.473 against 0.362. The new results give a more rapid falling off of compressibility at the high end of the range than formerly, which is in the direction which certain theoretical considerations had suggested as probable.

By far the most interesting of the new results is the volume discontinuity found for caesium at approximately 45,000, just at the end of the previous measurements. The single run previously made with increasing pressure just before the apparatus broke showed the same effect. The volume change is comparatively large, about 11 per cent. This volume change is in addition to the one already known at about 23,500 kg/cm² (5), at which occurs a change from the body centered to presumably the face centered arrangement, according to the calculations of Bardeen (6). The new transition must therefore be from

an arrangement which is already close packed to something else; the question is what can it be. The new transition is clean cut, reversible, and runs rapidly in either direction with little pressure transgression. Above the transition the new modification of caesium has, in comparison with the other alkalis, an unexpectedly small compressibility, which drops off abnormally rapidly with increasing pressure. In the table a reversal in the trend of the compressibility to drop with increasing pressure is indicated at the last interval between 90,000 and 100,000. This may or may not be real; the figures were given as they came without final smoothing.

Other Elements. In Table II the volumes of 17 other elements are given up to 100,000. In general those elements were chosen which had not already been measured which have a compressibility large enough to be inviting. A five per cent change of volume at the maximum pressure is about the minimum that should be attempted—ten per cent is better. In addition to these a number of elements were tried whose position in the periodic table suggested them as candidates for polymorphic transitions.

Detailed comment on the elements of Table II now follows.

Beryllium. The material I owe to Professor John Chipman of M. I. T. The purity is said to have been about 99.7 to 99.8 per cent with possible inclusion of oxygen. It was from the same batch as a specimen whose tensile behavior under pressure has been reported elsewhere (7). Beryllium is the most incompressible of the elements examined here. Acceptance of the data at their face value would indicate a compressibility increasing with pressure. This was not borne out, however, by the independent measurements in the 40,000 apparatus. The best course is to assume a linear relation between pressure and volume between 25,000 and 100,000. The table does not list the intermediate volumes in order to give no false impression about the accuracy. The most important result is that there is no marked transition below 100,000.

Carbon (graphite). The material was single crystal Ceylon graphite in sheets of the order of .005 inches thick which I owe to the courtesy of Sir K. S. Krishnan a number of years ago. It was cut into discs with a tubular cutter. The discs were then stacked and assembled in the indium sheath. Measurements have been previously made and published on the same material to 25,000 (8); measurements were not now re-

TABLE II
VOLUME OF VARIOUS ELEMENTS

Pressure kg/cm ²	Be	C (Graphite)	Mg	Al	Si	Phosphorus Black Violet	Ti	Mn	Ge	As	Zr	La	Ce	Pr	Nd	Th	U
1	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
25,000	.978	.947	.943	.970	.978	.935	.903	.961	.968	.955	.974	.917	.797	.927	.935	.962	.978
30,000		.940	.935	.966	.974	.927	.885	.956	.964	.947	.967	.904	.788	.916	.925	.952	.973
40,000		.929	.919	.958	.968	.912	.853	.947	.956	.933	.956	.882	.770	.896	.906	.937	.966
50,000		.919	.904	.951	.962	.899	.829	.939	.949	.921	.946	.863	.756	.878	.889	.924	.960
60,000		.911	.890	.944	.957	.837	.809	.932	.942	.911	.937	.846	.744	.863	.873	.913	.955
70,000		.903	.878	.937	.952	.825	.793	.926	.935	.903	.929	.832	.732	.849	.858	.904	.951
80,000		.896	.866	.929	.948	.816	.780*	.922	.929	.896	.922	.819	.722	.836	.845	.897	.947
90,000		.890	.856	.922	.944	.807	.667	.918	.923	.890	.916	.808	.714	.823	.833	.891	.944
100,000	.945	.885	.847	.915	.940	.799	.660	.915	.917	.884	.910	.798	.708	.811	.822	.886	.941

† Reversible transition to black. Volumes: 0.773 and 0.670
 * Irreversible transition at 85,000 from violet to black.

peated in the 40,000 apparatus. The results should be fairly good, because the slope of the curve obtained with the 25,000 apparatus fits on smoothly with the results now found.

Magnesium. This was from stock obtained a number of years ago from the Research Laboratory of the Aluminum Company of America and had been especially purified. It was used directly, without the intervention of an indium sheath, the mechanical softness being sufficient. The results therefore do not depend on any corrections for the effect of the sheath. The compressibility has been previously measured (9) only to 12,000 kg/cm². The fiducial volume at 25,000 was assumed to be 0.943 by extrapolation of the former results according to the formula:

$$-\Delta V/V_0 = 29.50 \times 10^{-7} p - 26.7 \times 10^{-12} p^2.$$

The slope at 25,000 of the new results agrees as well as could be expected with the extrapolated slope, being 0.017 against 0.016.

Aluminum. The material was cut from a Bureau of Standards melting point sample. Four runs were made: two with an indium sheath and two without. The agreement between the two sets was not as good as desirable, the volume at 100,000 given by the former being 0.903 against 0.915 by the latter. The latter was made the basis of the results in the table, since it is presumptively more correct because of the absence of correction for the sheath. The variation of compressibility given by this series, however, is presumptively not correct, a slight increase of compressibility with increasing pressure being indicated, in opposition to the definitely indicated decrease of compressibility of the much more accurate measurements by the method of linear compressibility, as yet unpublished, to 30,000. The course was therefore adopted of showing a linear decrease of volume in the table between 25,000 and 100,000.

Silicon. This material I owe to the kindness of Dr. W. Shockley of the Bell Telephone Laboratories; it had been highly purified. There are no previous measurements of the volume to high pressures. The fiducial volume at 25,000 was calculated from the absolute potentiometer setting at contact. This value lies smoothly enough between the atmospheric volume and the values at higher pressures. The only previous determination of the compressibility of silicon appears to have been by T. W. Richards (10) over a pressure range of 500 kg/cm²; his value was 3.1×10^{-7} . This is much lower than the value indicated by

this new work. The early specimens of silicon were notoriously impure, and inadequate impurity is doubtless the major source of the discrepancy.

Phosphorus. 1. *Black phosphorus.* This was from my old stock, made from yellow phosphorus at 12,000 kg/cm² and 200° C. some 20 years ago. There are no other measurements of the volume at high pressures. The fiducial volume at 25,000 necessary in the present calculations was taken from the absolute potentiometer setting. Black phosphorus has a transition with comparatively large change of volume which runs with increasing pressure at 55,000 or 60,000. The reverse transition, however, with decreasing pressure does not run above 25,000, and therefore was not observable with the present set-up. The fact that it does run, and that the transition is therefore of the thermodynamically reversible type, was established in two ways: by the return of volume to normal value at atmospheric pressure and subsequent repetition of the entire pressure cycle when the measurements were repeated on the same sample in the second piezometer, and by X-ray determinations of the structure of the material after exposure to 100,000. The X-ray examination was most kindly made by Professor B. F. Warren of M. I. T., who found the same normal black phosphorus structure which he had previously determined. In the table the transition pressure is indicated as 50,000; this can be only rough. It is probably much closer to the lowest pressure at which the transformation runs spontaneously with increasing pressure than to the pressure of thermodynamic equilibrium. Naturally the volumes indicated in the table for the low pressure phase had to be obtained from the readings with increasing pressure only, instead of being an average of increasing and decreasing as usual.

2. *Violet phosphorus.* This also was from my old stock, formed at about the same time as the black phosphorus and described in previous publications (11). Only one run was made with this, and the volumes in the table are obtained from the readings with increasing pressure only. This was necessary because between 80,000 and 90,000 the violet is transformed irreversibly to black, as is indicated in the table. The identity of the transformation product was again most kindly established by Professor Warren by X-ray analysis, who found the conventional black phosphorus lines, but much broadened, indicating a fine grained and distorted structure, as would be expected from the manner of formation. Profes-

sor Warren also made an X-ray examination of the original violet phosphorus and found a line pattern somewhat better developed than the line pattern of many other varieties of red phosphorus. Up to the present, however, he has not been able to index the pattern of either this or any of the other varieties so that for the present the exact identity of this material is not known.

The markedly greater compressibility of violet phosphorus in comparison with black is to be noted. This is in the direction to be anticipated. The transformation of violet to black phosphorus has already been accomplished at a pressure of 40,000 kg/cm² combined with plastic flow in shear (12). The transformation found in this paper is the first time that it has been accomplished by pure hydrostatic pressure. The great efficacy of shearing stress in promoting a transition which is thermodynamically possible but which is resisted by internal viscosity is apparent.

Titanium. This was from a lot recently obtained from A. D. Mackay, said to be of 99 per cent purity. It was hard and brittle, and was one of the most incompressible of the substances measured here. As in the case of beryllium, the measurements taken at their face value indicate a compressibility which is least at the lower end of the range, increasing somewhat to a roughly constant value at pressures over 50,000. This is not in line with the results obtained with the 40,000 apparatus, which indicated a normal decrease of compressibility with rising pressure up to 40,000. The best that can be done with the present results is to assume a linear relation between volume and pressure up to 100,000, and to take the volume actually obtained at 100,000 as giving the best mean compressibility. The most important result is that there is no large transition. Only a single piezometer was used.

Manganese. This material was obtained through the kind offices of Dr. B. A. Rogers before the war from the U. S. Bureau of Mines in Salt Lake City. The analysis given was 1.02% Ni, 2.33% Cu, 0.1% Si, balance Mn. The compressibility was not measured in the 40,000 apparatus; the fiducial volume at 25,000 was obtained from the absolute potentiometer setting. The compressibility thereby indicated for the low pressure end of the range fits on smoothly with that obtained with the present apparatus above 25,000. In view of the complicated crystal structure of manganese it might perhaps have been anticipated that it would exhibit transitions.

Perhaps the comparatively large amount of copper may have suppressed such a transition.

Germanium. This I owe to the kindness of Professor Lark-Horovitz. It had been used by him in his low temperature investigations of the Hall effect and was of his "N" type. This was measured also in the 40,000 apparatus; the volume at 40,000 obtained with it was 0.952 against 0.956 above.

Arsenic. This was from my single crystal stock, the same as that used in previous measurements (13), and known to be of high purity. The effect of pressure on this substance is known to be complicated; measurements of the linear compressibility to 12,000 kg/cm² indicated great differences in different directions and a condition of not well defined internal equilibrium. The volume compression has been measured to 25,000 and the fiducial volume at 25,000 was taken from those measurements (3)—no measurements were made with the same apparatus to the new range of 40,000. The present results do not join on quite smoothly with the former ones to 25,000, the new ones giving a higher compressibility at the low end of the range. The former results gave a volume decrement between 20,000 and 25,000 of 0.0062, and the new results between 25,000 and 30,000 of 0.075. There was no perceptible permanent change of volume after the first application of 100,000.

Zirconium. This was from the same specimen as that previously measured (14) to 12,000. It was obtained from the laboratory of the Philips Lamp Works in Eindhoven, was soft and malleable and presumably of high purity. Measurements to 100,000 were made in only a single piezometer. The fiducial volume at 25,000 was obtained from measurements with the 40,000 apparatus. This gave for the volume at 40,000 0.960 against 0.956 above. No transition was found; the compressibility drops smoothly with increasing pressure.

Lanthanum. This was obtained from Mackay, without statement of the probable purity. It was shipped under oil to avoid oxidation, was soft, and had every appearance of sound, homogeneous, pure metal. This was the first measured of four rare earth metals in consecutive places in the periodic table, namely La, Ce, Pr, and Nd. Very little work has been done on these previously under pressure. Cerium, however, is known (15) to be anomalous, having a rather large transition near 7,000 and the low pressure phase, being one of the few substances with a com-

pressibility increasing with increasing pressure. It suggested itself that the other rare earth metals might also show abnormalities; the only one found was a transition of lanthanum with .0026 volume change at 23,400 kg/cm².

Measurements were made on lanthanum to 100,000 in only a single piezometer. It was also measured in the 40,000 apparatus and the fiducial volume at 25,000 obtained from those measurements. Since lanthanum is among the more compressible of the substances measured here the results may be accepted with some confidence. The volume at 40,000 given by the 40,000 apparatus was 0.881 against 0.882 above.

Cerium. This was obtained from Mackay at the same time as the lanthanum and the same remarks apply to it. Measurements in the 40,000 apparatus gave for the volume at 40,000 0.766 against 0.770 above. It will be seen that no new anomalies were found above the transition, and the compressibility of the high pressure phase decreases normally with increasing pressure. The data to 40,000 should be consulted; they differ materially at low pressures from the previous data.

Praseodymium. This was obtained from Mackay and the same remarks apply as to lanthanum and cerium. Measurements were made in both the 40,000 and the 100,000 apparatus; for the latter only a single piezometer was used. No anomalies were found, at either high or low pressures. The volume at 40,000 given by the 40,000 apparatus was 0.893 against 0.896 with the 100,000 apparatus.

Neodymium. This was also obtained from Mackay, and the same remarks apply as to the three other rare earth metals. Measurements to 100,000 were made in only a single piezometer. The volume obtained with the 40,000 apparatus at 40,000 was 0.905 against 0.906. No anomalies were found in any part of the range.

Thorium. This was also obtained from Mackay. It was in the form of rolled sheet, 0.004 inches thick. The purity was not stated. It was punched into discs, which were stacked for the measurements to 100,000, using an indium sheath as usual. Only a single piezometer was used to 100,000 and no measurements were made with the 40,000 apparatus. No anomalies were found in the high pressure range. The compressibility of thorium has been previously measured (16) to 12,000 for which the formula was found:

$$\Delta V/V_0 = -18.15 \times 10^{-7} p + 11.22 \times 10^{-12} p^2.$$

The fiducial volume at 25,000, 0.962, was obtained by extrapolation from this formula. At 50,000 the same formula gives 0.912 against 0.924 found above.

Uranium. This was old stock of unknown origin which I had had for a number of years. It is one of the more incompressible of the elements measured here, so that the results are relatively less reliable. The behavior found was normal in every respect. Uranium is mechanically much softer than either beryllium or titanium, and no indication of an anomalous increase of compressibility was found. The fiducial volume at 25,000 was obtained from the 40,000 apparatus, which gave for the volume at 40,000 0.9676 against 0.966 above.

Certain Compounds. In Table III the volumes

the neighborhood of 40,000. This transition was perceptible in the readings with increasing pressure with one of the piezometers, but not with the other, which was more irregular than usual. The results in Table III are accordingly smoothed over the transition. At 50,000 the former value of the volume was 0.907 against 0.922 given now. The difference is greater than usual and is doubtless connected with smoothing over the transition.

The measurements with HgS were not as satisfactory as desirable. The material was the red sulfide, previously used to 50,000. The first run to 100,000 gave an abnormally high compression up to 80,000, and then a further volume discontinuity indicating a transition. Unfortunately the slider stuck because of viscosity in the transmitting medium (this was before this defect in

TABLE III
VOLUME OF VARIOUS COMPOUNDS

Pressure kg/cm ²	ZnS	ZnSe	ZnTe	HgS	HgSe	HgTe	PbS	PbSe	PbTe
1	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
25,000	.972	.955	.950	.922	.853	.870	.933	.938	.944
30,000	.968	.950	.944	.920	.844	.863	.928	.932	.939
40,000	.961	.940	.933*	.916	.829	.847	.918	.922	.930
50,000	.954	.930	.922	.912	.816	.832	.909	.888*	.884*
60,000	.947	.921	.911	.906	.805	.817	.900	.877	.869
70,000	.940	.912	.899	.899	.795	.803	.892	.867	.855
80,000	.934	.904	.888	.892	.788	.790	.886	.858	.842
90,000	.929	.895	.878	.885	.782	.777	.881	.849	.831
100,000	.924	.887	.868	.879	.777	.765	.876	.841	.820

* Small
transition
at 38,000

* Small
transition
here

* Transition
at 45,000.
Vols. 0.917
and 0.893

* Transition
at 45,000.
Vols. 0.925
and 0.892

of nine compounds are given: the sulfides, selenides and tellurides of zinc, mercury and lead. These have already been measured (17) to 50,000; the material used in the new measurements is the same as that of the old.

ZnS was measured in the form of sphalerite; the form wurtzite is known to be changed by pressure and shear irreversibly to sphalerite (18). Nothing notable was found in the new range. At 50,000 the volume was formerly found to be 0.951, to be compared with 0.954 found now.

ZnSe was formerly found to have a transition in the neighborhood of 38,000 kg/cm² with volume discontinuity of .004. This is too small to be definitely indicated in the present results, which were smoothed right over the transition. The volume at 50,000 given by the previous measurements was 0.931 against 0.930 now.

The former measurements on ZnTe gave a transition with volume discontinuity of 0.005 in

the apparatus had been corrected) with decreasing pressure, and the results of the run were discarded. The run with the second piezometer gave perfectly satisfactory readings on the identical specimen, except that the compression was markedly less. One would suspect a permanent change of form after the first application, except that recovery of the initial volume at atmospheric pressure had been perfect. The present measurements indicate an increase of compressibility with pressure at the low end; it is questionable how much of this is real. The volume found in the former measurements at 50,000 was 0.892 against 0.912 found now. The difference is larger than usual and again indicates some unusual occurrence; X-ray analysis of the final product would be desirable.

The HgSe was material which had previously been exposed to 50,000. It is known to have a large transition near 7,500; which naturally did

not figure in the present work. The volume previously found at 50,000 was 0.820 against 0.816 found now. The high pressure measurements seem conventional enough; the decrease of compressibility with increasing pressure is perhaps somewhat greater than normal.

The HgTe was from the same batch of synthetic material as that formerly used, but this particular piece had not been formerly exposed to pressure. It was previously found that HgTe decomposes slowly under pressure to the elements. This decomposition prevented former measurements of the compressibility, but did not prevent the establishment of a reversible transition near 12,000 with 8.4 per cent volume change, slightly less than the change of HgSe. In this new work the decomposition was not encountered, doubtless because the volume was so much smaller and the application of pressure so much more rapid, 20,000 in the preliminary application being reached in two or three minutes. As a consequence of this there are no low pressure compressibilities which could be used by extrapolation nor any direct measurements to give the fiducial volume at 25,000. The value used in the table, 0.870, is a guess based on the known volume of HgSe and the known volume discontinuities at the transitions. The high pressure measurements appear normal enough. The compressibility at high pressures drops off with increasing pressure much less than it does for HgSe, and the volume curves cross.

The PbS was a piece which had been previously exposed to 50,000. It is known that there is a transition just below 25,000, which naturally did not appear in this work except as it enters the fiducial volume at 25,000, which was taken from the former measurements. The volume at 50,000 given by the former measurements was 0.901 against 0.909 found now.

PbSe has been previously found to have a polymorphic transition at 43,000 with volume discontinuity of 0.016. The transition was found with these new measurements with a somewhat larger volume change, 0.024. The new value is doubtless to be preferred, since the transition point is so near the end of the former pressure range that the transition may not have run to completion. The volume at 50,000 given by the previous measurements was 0.882 against 0.888 found now. Above the transition the compressibility falls off normally with increasing pressure. The compressibility of the high pressure phase is

not markedly different from that which would be extrapolated from the low pressure phase.

The PbTe had not been used in the former measurements to 50,000 but had been seasoned by an application of 30,000. Again, as in the case of PbSe, the previous measurements showed a transition at about 42,000. The volume change found was 0.009. The transition was found in the present work, but with a much larger volume change, 0.033. Doubtless the former low value is to be explained by incomplete running of the transition. The volume previously found at 50,000 was 0.900 against 0.884 found now. The difference can be almost entirely explained by former incomplete running of the transition.

Quartz Crystal and Six Glasses. One point of interest in measuring the glasses was to find whether the abnormal increase of compressibility with increasing pressure found at low pressures persists at high pressures. In the case of quartz glass it had already been found (19) that there is a reversal near 35,000. The interest in measuring quartz crystal was to compare it with the glass. The three glasses "A", "C", and "D" in the following were from the same stock as that used in previous measurements (20) of the effect of pressure on rigidity. The glass was originally obtained from Dr. J. T. Littleton of the Research Laboratory of the Corning Glass Works. "A" was a potash lead silicate of very high lead content, "C" was a soda potash lime silicate, and "D" a soda zinc borosilicate. The quartz glass was from ordinary laboratory stock, selected to be free from visible imperfections. The quartz crystal was provided by Professor Birch, who had it worked to the special shape required for measurement in the 40,000 apparatus. After the measurements to 40,000 I cut from the specimen a smaller piece for measurement to 100,000. The borax glass was also provided by Professor Birch, from the same stock as that used by Dane and Birch in their measurements of the effect of pressure on viscosity (21).

The volume at 40,000 for quartz crystal found with the 40,000 apparatus was 0.921, against 0.926 given by the 100,000 measurements. The cubic compressibility of quartz crystal is also obtainable from previous measurements (22) of the linear compressibilities in different directions up to 12,000. The formula, corrected for my improved compressibility of iron, is:

$$\Delta V/V_0 = -26.45 \times 10^{-7}p + 22.6 \times 10^{-12}p^2.$$

This formula gives by extrapolation for the

TABLE IV
VOLUME OF QUARTZ CRYSTAL AND SIX GLASSES

Pressure kg/cm ²	Quartz Crystal Glass		Glass "A"	Pyrex Glass	Glass "C"	Glass "D"	Borax Glass
1	1.000	1.000	1.000	1.000	1.000	1.000	1.000
25,000	0.946	.923	.934	.921	.945	.932	.877
30,000	.939	.909	.923	.907	.936	.924	.866
40,000	.926	.885	.905	.885	.920	.909	.845
50,000	.914	.864	.890	.867	.905	.894	.825
60,000	.902	.847	.875	.851	.891	.880	.808
70,000	.892	.832	.862	.838	.878	.867	.792
80,000	.883	.819	.849	.827	.866	.855	.778
90,000	.875	.808	.838	.817	.854	.844	.765
100,000	.868	.798	.828	.809	.842	.834	.753

volumes at 25,000, 30,000, and 40,000: 0.948, 0.942, and 0.930 respectively. The agreement with the values of Table IV is as close as could be expected for an extrapolation of this magnitude.

Quartz glass, measured in the 40,000 apparatus, gave for the volume at 40,000 0.881 against 0.885 in Table IV. Measurements have also been previously made to 50,000. The previous volumes at 25,000, 30,000, 40,000, and 50,000 respectively were 0.928, 0.912, 0.884, and 0.861. Both the previous measurements to 50,000 and the new ones to 40,000 show well the reversal in $\left(\frac{\partial^2 v}{\partial p^2}\right)_T$ near 35,000. The measurements in Table IV to 100,000 do not show this so well, however, the point of reversal being too near the lower end of the range. It will be noticed that the compressibility of the glass drops off with increasing pressure, in the range above 40,000 where it has become normal, more rapidly than that of the crystal. This is to be expected.

The volume of glass "A" given by measurements in the 40,000 apparatus was 0.904 at 40,000 against 0.905 found now. The 40,000 measurements indicate a break in direction near 20,000, the glass being more compressible above this pressure than would have been extrapolated from the volumes at lower pressure. This behavior is not suggested by anything in the present range, the compressibility dropping off smoothly with increasing pressure.

Pyrex glass has been found previously to have the same abnormal increase of compressibility with pressure as exhibited by quartz glass. Previous measurements had not extended above 12,000. New measurements on pyrex up to 40,000 show that the anomaly vanishes in the neighborhood of 25,000. The volume at 40,000 found with the 40,000 apparatus was 0.887 against 0.885 of Table IV above. In the range

of Table IV compressibility drops normally with increasing pressure.

Glass "C" measured in the 40,000 apparatus shows the same sort of anomaly in the neighborhood of 20,000 as glass "A." The behavior appears to be normal in the range above 25,000 covered in Table IV. The volume at 40,000 found with the 40,000 apparatus was 0.917 against 0.920 found above.

Glass "D" measured in the 40,000 apparatus shows the same type of anomaly as "A" and "C," except that it is even more pronounced and occurs at a pressure somewhat below 20,000 instead of above it. The volume at 40,000 given by the 40,000 apparatus was 0.895 against 0.909 above. The discrepancy is by far the largest of any found in this paper. All the measurements appeared normally good, and the explanation does not suggest itself. If the anomaly just below 20,000 were associated with a transition, and if this were suppressed in the high pressure measurements, perhaps because of the rapidity with which pressure was increased, the discrepancy would be qualitatively explained. However, a transition of this sort in a glass would be something new.

Borax glass, measured in the 40,000 apparatus, showed no low pressure anomalies. The relation between volume and pressure is definitely not reproducible by a second degree expression in the pressure, the initial rate of drop of compressibility compared with that at higher pressures being too high. At 40,000 the volume given by the 40,000 apparatus was 0.835, against 0.845 above. The discrepancy is larger than usual, but so also is the absolute change of volume. Borax glass is the most compressible of the glasses measured here; quartz glass is next. The shape of the curves of volume against pressure is not the same for these two glasses; they draw together between 25,000 and 50,000, and from 50,000 on draw apart again by a small amount.

DISCUSSION

Perhaps the most interesting question raised by an extension of volume measurements into a new field of high pressure is whether there is any indication of the atomic break-down to be expected at astronomical pressures. Ultimately, at high enough pressures, it has been shown by Jensen (23) and others that the perfect gas law will be followed, or volume will be inversely as the pressure. This means that ultimately $\log \text{vol}$ will be linear in $\log p$, with a slope of unity. In Figure 5, $\log_{10} \text{vol}$ is plotted against $\log_{10} p$ for the five alkali metals of this paper, for lanthanum, the next most compressible metal of this paper, for borax glass, and for CsBr, one of the most compressible of the salts, the data for which have been determined in a previous paper (24). With one exception, the curves are all concave downward. If curvature continues in this direction, the volume will vanish at infinite pressure. Asymptotic approach to a finite volume at infinite pressure would obviously demand a reversal of curvature. Now all the early equations of state, before the possibility of atomic disintegration was visualized, demanded almost without exception a finite limiting volume at infinite pressure. These high pressure measurements are sufficient to show the definite inadequacy of this point of view. Further than this, the curves do not suggest any very definite conclusions. They are obviously still a long way from approaching the limiting slope of unity, and might equally well be headed for other limiting slopes, which would mean that ultimately the volume becomes proportional to some power of the pressure other than the first.

Especial significance should doubtless be attached to the curve for caesium. There are two breaks in this curve corresponding to the two polymorphic transitions. The lower transition at 23,000 has a small volume change and the course of the curve is hardly affected on passing through it. The higher transition at 45,000, however, is something quite different. The volume change is much larger, and the high pressure phase is drastically different, because for it $\log \text{vol}$ against $\log p$ is concave upward, the only example of it. This is the direction of curvature consistent with a finite volume at infinite pressure, and is not the sort of thing associated with the atomic breakdown contemplated by Jensen. A plausible inference would seem to be that there may be a large number of

intermediate episodes on the way to complete atomic disintegration. It seems not unreasonable to expect that the pressure domain beginning at roughly 10^5 or 10^6 atmospheres may be a domain of as much detail and structure, at present entirely unsuspected by us and beyond present theoretical attack, as the complex atomic domain of ordinary experience.

The high pressure end of the curve for potassium shows indications of an approaching reversal of curvature like that of caesium. Experimental error, however, makes this more uncertain; the large effect for caesium would seem to be beyond possible experimental error.

The curves for borax glass and for caesium bromide cross; that of the latter runs roughly parallel with that of the metals. The crossing indicates an abnormally high compressibility in the borax glass at the low pressure end of the range. This is what might be expected in a glass, the initial effect of increasing pressure being to remove the "slack" between the molecules, as in a liquid.

Incidentally, any crossing of the volume curves is inconsistent with a universal one parameter relation between volume and pressure, of which the simple one constant equation of Murnaghan (25) is a recent example. Murnaghan's more complicated equations, with two or more disposable constants, would be required to represent all the present results.

REFERENCES

1. P. W. Bridgman, Proc. Amer. Acad. 74, 425-440, 1942; 76, 1-7, 1945.
2. P. W. Bridgman, Jour. App. Phys. 18, 246-258, 1947.
3. P. W. Bridgman, Proc. Amer. Acad. 76, 9-24, 1945.
4. First reference under 1, p. 434.
5. P. W. Bridgman, Proc. Amer. Acad. 72, 183, 1938.
6. J. Bardeen, Jour. Chem. Phys. 6, 372-378, 1938.
7. Reference (2), p. 251.
8. Reference (3), p. 17.
9. P. W. Bridgman, Proc. Amer. Acad., 66, 261, 1931.
10. T. W. Richards, Jour. Amer. Chem. Soc. 37, 1646, 1915.
11. P. W. Bridgman, Journ. Amer. Chem. Soc. 36, 1344-1363, 1914; 38, 609-612, 1916.
12. P. W. Bridgman, Proc. Amer. Acad. 71, 424, 1937.
13. P. W. Bridgman, Proc. Amer. Acad. 68, 39, 1932.
14. P. W. Bridgman, Proc. Amer. Acad. 63, 348, 1928.
15. P. W. Bridgman, Proc. Amer. Acad. 62, 211, 1927.
16. Reference (15), p. 217.

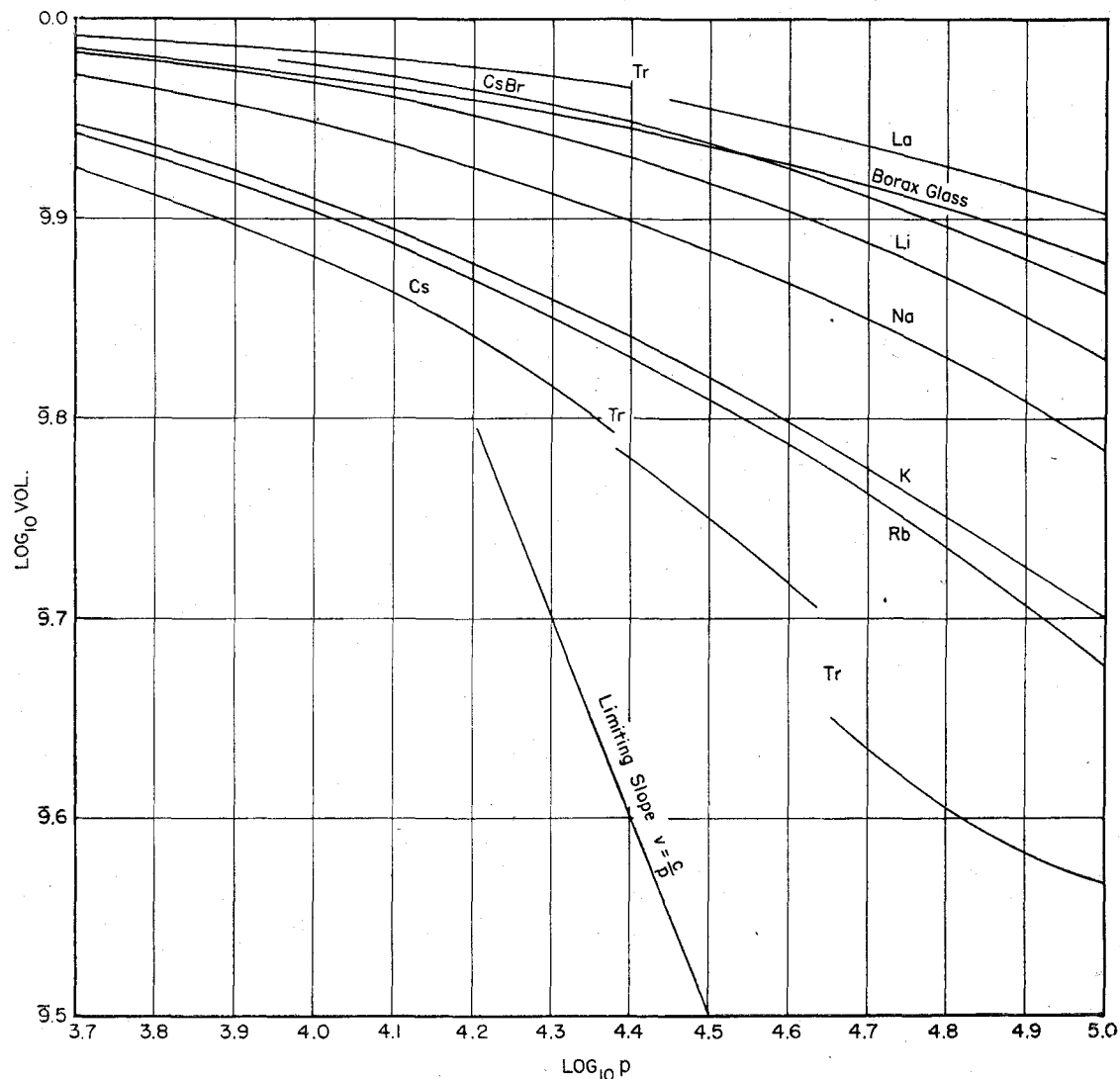


FIGURE 5. Logarithm of the volume against logarithm of the pressure up to 100,000 kg/cm² for a range of substances.

REFERENCES—*Cont.*

17. P. W. Bridgman, Proc. Amer. Acad. 74, 21-51, 1940.
18. P. W. Bridgman, Amer. Jour. Sci., 237, 18, 1939.
19. Reference (18), p. 13.
20. P. W. Bridgman, Proc. Amer. Acad. 63, 409, 1929.
21. E. B. Dane, Jr. and Francis Birch, Jour. App. Phys. 9, 669-674, 1938.
22. P. W. Bridgman, Amer. Jour. Sci., 10, 491, 1925.
23. H. Jensen, ZS. f. Phys. 111, 373-385, 1938. ZS. f. tech. Phys. 19, 563-565, 1938.
24. Second reference under (1), p. 4.
25. F. D. Murnaghan, Proc. Nat. Acad. Sci. 30, 244-247, 1944.

ROUGH COMPRESSIONS OF 177 SUBSTANCES TO 40,000 KG/CM²

By P. W. BRIDGMAN

Presented Oct. 25, 1947.

Received Oct. 25, 1947.

TABLE OF CONTENTS

Introduction.....	71
Detailed Data.....	71
Plastics.....	71
Glasses.....	74
Elements.....	75
Minerals.....	77
Substances with Transitions.....	78
Miscellaneous Compounds.....	81
Compounds with Ortho-, Meta-, and Para- Forms.....	83

INTRODUCTION

In a previous paper (1) an apparatus has been described for the rapid determination of the compression of solids at room temperature to high pressures, and the compression of 61 fairly compressible solids determined with it to 25,000 kg/cm². It was definitely not the intention to push this apparatus to the limit, but to use it as a tool of routine exploration in a range in which there would be no danger of fracture. It now appears that the limit formerly set was too conservative, for the same apparatus with minor modifications has now been carried regularly to 40,000, and the compression of 177 substances determined with it. Each substance involves two applications of maximum pressure, a preliminary "seasoning" application and the second stepwise application, up and down in steps of approximately 2,000 kg/cm², giving 43 readings in all. This has been accomplished with no fracture or measurable change of dimensions of the main pressure vessel. The short carboly pistons, however, with which pressure is produced do not stand up indefinitely in this higher range, but have to be renewed from time to time. Failure of the piston is foreshadowed by the appearance of minute cracks, and since the piston can still be used several times after the first cracks appear, this has proved no disadvantage. One catastrophic failure occurred in the course of this new work. This was a failure of the steel column by which pressure is transmitted to the short carboly piston, the column having been designed for the lower range of 25,000.

Fortunately it was possible to redesign the column for the higher pressure range, and no further trouble has been encountered.

The materials investigated in the following have been selected as of interest from several points of view. The accuracy of the measurements naturally is greater for the more compressible substances, so that, in general, highly incompressible substances are to be avoided. Even these may be examined with profit, however, with regard to the possible existence of new polymorphic forms. There is no one guiding motif in the selection of the following material. The measurements have been made rather in the spirit of "scientific knitting," done in spare time between more systematic and important investigations. Since these measurements are mostly new, it has seemed worth while to at least record them.

The detailed presentation of data now follows, grouped into classes of substances.

Detailed Data

Plastics. Some 38 different plastics were measured, collected from a number of sources to have as wide a range of composition as possible. It was anticipated that there might be various transitions of higher orders among the plastics, that is, discontinuities in the various derivatives of volume, as a result of different stages of alignment of the long molecules. This did not turn out to be the case, however, but the curves were in almost all cases smooth.

The first six plastics shown in Table I were ordinary articles of commerce, taken from the laboratory stock. The Bakelite was clear amber stock, perhaps 25 years old. The "new" hard rubber was perhaps two or three years old, and the "old" about 25 years old. The purpose in trying rubber of two ages was to test whether there is any slow change with time. I owe to the courtesy of the du Pont Company the specimens of nylon and "Teflon" (polytetrafluorethylene), No. 29 in the table. The nylon 6-10 was cut from a sheet about 0.25 inch thick. The

TABLE 1
COMPRESSION OF VARIOUS PLASTICS

Pressure kg/cm ²	Leu- cite	Poly- styrene	Cellu- lose Ace- tate	Bake- lite	Hard Rubber new	Hard Rubber old	Nylon 6-10	Nylon 6-6 unori- ented	Nylon 6-6 ori- ented	α- Beetle Filler	Aero- glass 4121	Lami- nac 4201	Mel- mac 404	Mel- mac 1079	Mel- mac S-6004	48,000	41,000	46,000	2060-38
0	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000
2,500	.0367	.0409	.0468	.0240	.0316	.0360	.0385	.0331	.0380	.0241	.0437	.0350	.0226	.0237	.0182	.0313	.0279	.0347	.0370
5,000	.0671	.0724	.0784	.0438	.0610	.0642	.0655	.0594	.0665	.0439	.0712	.0599	.0421	.0434	.0331	.0545	.0510	.0619	.0656
10,000	.1097	.1200	.1189	.0760	.1045	.1068	.1060	.0961	.1061	.0757	.1136	.0967	.0741	.0754	.0567	.0894	.0853	.1028	.1098
15,000	.1387	.1519	.1486	.1022	.1345	.1372	.1348	.1233	.1340	.1000	.1427	.1245	.0992	.1004	.0753	.1148	.1119	.1324	.1417
20,000	.1611	.1756	.1717	.1235	.1573	.1600	.1570	.1444	.1559	.1202	.1658	.1469	.1199	.1208	.0906	.1359	.1337	.1554	.1656
25,000	.1796	.1946	.1905	.1413	.1760	.1785	.1749	.1617	.1739	.1371	.1841	.1650	.1368	.1376	.1035	.1535	.1520	.1742	.1846
30,000	.1949	.2104	.2065	.1564	.1917	.1938	.1900	.1768	.1893	.1512	.1996	.1803	.1509	.1516	.1149	.1636	.1671	.1900	.2004
35,000	.2078	.2240	.2200	.1695	.2050	.2070	.2029	.1899	.2024	.1632	.2127	.1935	.1632	.1636	.1248	.1810	.1803	.2031	.2138
40,000	.2184	.2359	.2318	.1812	.2166	.2188	.2139	.2016	.2136	.1739	.2241	.2052	.1737	.1738	.1334	.1916	.1919	.2146	.2252

TABLE 1—Continued
COMPRESSION OF VARIOUS PLASTICS

Pressure kg/cm ²	M-1805	M-2348	M-1364	M-2347	M-2343	M-2345	M-2346	M-2344	M-2342	Teflon	Fluo- rine Plastic	Silicone 160	Silicone 181	Silicone 180	Silicone 167	Silicone 120	Silicone 125	Silicone 150	Silicone Glass filled
0	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000
2,500	.0553	.0548	.0522	.0435	.0424	.0399	.0399	.0435	.0474	.0527	.0398	.0835	.0746	.0653	.0669	.0814	.0872	.0737	.0334
5,000	.0874	.0897	.0863	.0760	.0762	.0707	.0707	.0781	.0775	.0847	.0673	.1182	.1090	.0967	.1001	.1213	.1284	.1112	.0580
10,000	.1319	.1331	.1300	.1201	.1217	.1156	.1156	.1262	.1213	.1453*	.1037	.1580	.1529	.1368	.1385	.1676	.1734	.1522	.0930
15,000	.1621	.1639	.1606	.1504	.1526	.1467	.1467	.1569	.1525	.1694	.1282	.1796	.1788	.1595	.1580	.1901	.1974	.1757	.1177
20,000	.1852	.1876	.1836	.1733	.1763	.1698	.1698	.1797	.1766	.1875	.1474	.1951	.1995	.1779	.1729	.2081	.2153	.1941	.1378
25,000	.2040	.2066	.2024	.1917	.1880	.1852	.1838	.1979	.1960	.2019	.1628	.2081	.2176	.1937	.1852	.2229	.2303	.2091	.1551
30,000	.2194	.2222	.2178	.2074	.2108	.2038	.2130	.2118	.2143	.2143	.1755	.2194	.2336	.2076	.1960	.2351	.2429	.2230	.1703
35,000	.2321	.2351	.2306	.2206	.2178	.2234	.2167	.2262	.2250	.2248	.1862	.2297	.2475	.2197	.2055	.2455	.2531	.2350	.1835
40,000	.2430	.2460	.2416	.2315	.2293	.2336	.2275	.2375	.2362	.2339	.1956	.2390	.2592	.2303	.2139	.2545	.2614	.2424	.1955

* Transition at 6,500.
Vols. 1004 and 1230

nylon 6-6 was provided in a rod of approximately 0.5 inch diameter (unoriented). The "oriented" specimen of this 6-6 nylon was produced by upsetting a cylinder originally 1 inch long by one-sided compression between the platens of a hydraulic press until the thickness was reduced to 0.085 inch. It required about 45,000 psi to do this. Plastics 10 to 15 inclusive I owe to the courtesy of the American Cyanamid Company. Their description of them is as follows:

Melmec 404; Melamine-formaldehyde, no filler, at present an experimental product.

Melmec S-6004; Melamine-formaldehyde, asbestos filler.

Melmec 1079; Melamine-formaldehyde, alpha cellulose filler.

Beetle; Urea-formaldehyde, alpha cellulose filler.

Aeroglass 4121; Clear cast copolymer type, no filler.

Laminac 4201; Clear cast copolymer type resin similar to that used in laminating applications, no filler.

Plastics 16 to 28 inclusive I owe to the kind offices of Dr. C. O. Strother of the Linde Air Products Company, who obtained most of them from the Bakelite Corporation. The description is given in the appended table.

In addition to the plastics described in detail in the above table, four others obtained from Dr. Strother are described as follows. "Sample 206-38 is of the type known as a polyester resin. It is generally made by the reaction of a di-basic acid containing maleic acid with a glycol. This base resin is hardened with a vinyl material such as styrene. The samples marked 41000 and 48000 are phenolic formaldehyde types. Sample 46000 is a so-called glyptal. It is made by the reaction of a di-basic acid, such as phthalic, with glycerine or a like compound."

Plastic 30 is one of the experimental fluorine plastics developed during the war which I owe to the kindness of Dr. W. T. Miller of Cornell.

Plastics 31 to 38 inclusive are various silicone plastics which I owe to the courtesy of the Dow-Corning Research Laboratory. These silicones are described by the manufacturers as "Silastics," and various mechanical and electrical properties are given in their trade catalogue on silicones. Silastics 120 and 125 contain approximately 50 per cent by weight of titanium oxide and 50 per cent of high polymeric methyl silicone. Silastics 160, 167, 180 and 181 contain approximately 60

Formulation				Properties of Base Resin				
Designation	Base Resin		Plasticizer (plus stabilizer)			Sp. Gr. 20/20	Vinyl Chloride Content, Wt. %	Average Mol. Weight
	Description	Wt. %	Vol. %	Description	Wt. %				Vol. %
M-1805	Polyethylene, Exp. low mol. wt.	100	100	—	—	—	0	14-16,000 (Soln. Viscosity)
M-2348	Polyethylene, Stand. DYNH	100	100	—	—	—	0	18-20,000 (Soln. Viscosity)
M-1364	Polyethylene Exp. high mol. wt.	100*	100*	—	—	—	0	36-38,000 (Soln. Viscosity)
M-2344	'Vinylite' VYHH Resin	98	97.5	Organo-tin heat stabilizer	2	2.5	87	55,000 (osmotic)
M-2345	'Vinylite' VYNS Resin	98	97.5	Organo-tin heat stabilizer	2	2.5	90	75,000 (osmotic)
M-2347	'Vinylite' VYNW-5 Resin	98	97.5	Organo-tin heat stabilizer	2	2.5	95	130,000 (osmotic)
M-2342	'Vinylite' VYNW-5 Resin	76.6	70	Organo-tin heat stabilizer	1.7	2.0	95	130,000 (osmotic)
				Diocetyl phthalate	21.7	28.0		
M-2343	'Vinylite' VYNW*-5 Resin	73.6	70.0	Organo-tin heat stabilizer	1.7	2.0	95	130,000 (osmotic)
				Tricresyl phosphate	24.7	28.0		
M-2346	'Vinylite' VYNW-5 Resin	76.0	70.0	Organo-tin heat stabilizer	1.7	2.0	95	130,000 (osmotic)
				Resinous Products G-25**	22.3	28.0		

Notes: *This resin contains an extremely small quantity of contaminating carbon arising in polymerization, hence, the dark gray color of molded plaque.

**Resinous type plasticizer reported to be a condensation product of sebacic acid, glycerol and ricinoleic acid.

per cent by weight of fillers and the balance is a high polymeric methyl silicone. The fillers are: 160—50 per cent zinc oxide and 50 per cent titanium oxide; 167—all titanium oxide; 180—50 per cent titanium oxide and 50 per cent silica; 181—all silica.

Omitting Melmac S-6004, a heavily filled plastic, and the filled α -Beetle, the range of volume compression under 40,000 is from .1737 for Melmac 404 to .2614 for Silicone 125-96, a range of about 50 per cent. The range of initial compressibilities is much wider than this, however. The volume compression in the first 2,500 kg/cm² varies from 0.0226 to 0.0872, a range of nearly four fold. That is, at the high pressures the initial differences tend to disappear. The silicones stand in a class by themselves, being characterized by a high initial compressibility. As already mentioned, no breaks in direction were found and the curves were all smooth. This does not mean, however, that the curves are all similar to each other, because a number of examples can be found of crossing of the curves. Any such effects are, however, not on a large scale.

The only anomaly found in all these plastics is shown by Teflon. This has, at 6,500 kg/cm², a discontinuity in volume, indistinguishable in all its traits of behavior from an ordinary reversible polymorphic transition. Since such transitions are ordinarily associated with change of lattice structure, and plastics are not, according to the ordinary point of view, endowed with a regular lattice structure, the occurrence of such a transition was unexpected. It would seem to indicate an unusually high degree of organization in the structure. Professor B. Warren, of Massachusetts Institute of Technology, was so kind as to make an X-ray analysis of a sample of teflon. He reported: "There are too many sharp lines for this to be classed as the pattern of a truly amorphous material. It is not possible to say that the material is perfectly crystalline, but it is closer to crystalline than to the completely amorphous state."

Glasses. Six glasses were measured, for which the results are given in Table II. Of these, quartz glass was from laboratory stock, selected to be free from internal striations. Pyrex was similarly selected from laboratory stock. Glasses "A," "C," and "D" are from the same rods as those used a number of years ago in measuring compressibility and the effect of pressure on rigidity (2). I owe them to the courtesy of Dr. J.

T. Littleton of the Research Laboratory of the Corning Glass works. Glass "A" is a potash lead silicate of very high lead content, "C" is a soda potash lime silicate, and "D" is a lead zinc borosilicate. The borax glass I owe to the courtesy of Professor Francis Birch; it is from the same batch as that used by Dane and Birch in their measurements of the effect of pressure and temperature on viscosity (3).

Of the six glasses investigated, all but the borax glass show anomalies of one sort or another which are all beyond any possible experimental error. The anomaly of quartz glass has already been investigated (4) in another apparatus up to 50,000. It was formerly found that its compressibility increases with increasing pressure at a constantly increasing rate until a pressure of 35,000, where there is a break in the direction of the tangent

TABLE II
COMPRESSION OF GLASSES

Pressure kg/cm ²	Quartz Glass	Pyrex	"A"	"C"	"D"	Borax Glass
0	.0000	.0000	.0000	.0000	.0000	.0000
5,000	.0141	.0153	.0159	.0121	.0144	.0345
10,000	.0295	.0308	.0300	.0239	.0281	.0631
15,000	.0452	.0465	.0425	.0352	.0411	.0857
20,000	.0610	.0622	.0535	.0449	.0542	.1054
25,000	.0772	.0786	.0656	.0549	.0678	.1228
30,000	.0933	.0920	.0770	.0654	.0806	.1376
35,000	.1068	.1032	.0866	.0742	.0927	.1518
40,000	.1194	.1133	.0964	.0830	.1049	.1648

(transition of the second kind in the nomenclature of Ehrenfest), and from there on decreases normally with further increasing pressure. This behavior is confirmed with the present apparatus. The discontinuity in direction is now found at a somewhat lower pressure, 31,000 instead of 35,000. The best way of seeing this is to plot the first differences of volume from Table II against pressure. With regard to absolute values, the volume decrement at 40,000 found with the present apparatus is 0.1194 against 0.1163 previously. This difference is not necessarily all instrumental, because there is reason to think that quartz glass is not a perfectly well defined substance. The anomaly of pyrex is similar in character to that of quartz glass, as is to be expected from the 81 per cent content of SiO₂ in pyrex. The break in direction is at a somewhat lower pressure for pyrex, between 28,000 and 29,000. Pyrex has been formerly measured (5) over the range up to 12,000, and the initial increase of compressibility with rising pressure

found. The volume decrement at 15,000, extrapolated from the 12,000 measurements, was 0.0462 against 0.0465 found now.

Glasses "A," "C," and "D" all show the same sort of anomaly, the reverse of that of quartz glass. It is natural to ascribe this to the silicate content of these glasses. The anomaly consists in a break in the direction of the tangent, but in the direction of an increase of compressibility rather than a decrease. Above and below the break the compressibility decreases normally with increasing pressure. For glass "A" the discontinuity in $\left(\frac{\partial v}{\partial p}\right)_T$ occurs at 21,000 and is ap-

proximately 0.00000045 in magnitude in the units of the table; for glass "C" it occurs at 22,000 and is 0.00000055 in magnitude, and for "D" it occurs at 18,000 and has a magnitude of 0.0000004.

The anomalies in quartz glass and the silicates are thus one the inverse of the other, and would therefore seem to imply inverse mechanisms. In the case of quartz some mechanism responsible for high compressibility goes out of action on reaching a certain pressure, and in the case of the silicates some new mechanism must come into action at a critical pressure. Mechanical models are not difficult to imagine. Thus if in the case of quartz the structure contained something analogous to dished flat springs, the increase of compressibility could be explained as a geometrical effect, the spring becoming flatter the further it was compressed and therefore offering less elastic resistance because of the diminishing arching effect, and the sudden termination of the effect could be explained by the opposite sides of the dished spring being compressed into mutual contact. In the case of the silicates an analogous sort of mechanism can be imagined, only now the springs are parallel to the direction of stress and the two leaves do not begin to separate until a crucial pressure is reached. The X-ray structure of the glasses is known to be complicated enough and also to have sufficiently marked partial regularities to make it not unpalatable to expect that mechanisms like these may exist.

Elements. The measurements on the elements were made both for their own sake, and also to provide the fiducial volume at 25,000 which was necessary in reducing the measurements to 100,000. These latter are reported in the previous paper; there is an overlapping range between 25,000 and 40,000 which affords a check on the measurements. The comparison of the measure-

TABLE III
COMPRESSION OF VARIOUS ELEMENTS

Pressure kg/cm ²	Lith- ium	Sodium	Potas- sium	Rubid- ium	Caesium	Beryl- lium	Tita- nium	Zinc	Germa- nium	Zirco- nium	Lan- thanum	Cerium	Praseo- dymium	Neo- dymium	Ura- nium
0	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000
2,500	.0204	.0334	.0677	.0696	.0999	.0024	.0027	.0040	.0040	.0026	.0100	.0109	.0090	.0078	.0024
5,000	.0389	.0624	.1152	.1224	.1585	.0047	.0052	.0079	.0078	.0054	.0194	.0234	.0174	.0152	.0048
10,000	.0715	.1115	.1862	.1982	.2392	.0094	.0099	.0154	.0152	.0111	.0370	.0549	.0329	.0289	.0095
15,000	.1005	.1511	.2374	.2506	.2981	.0139	.0143	.0225	.0213	.0168	.0526	.1655	.0471	.0416	.0139
20,000	.1261	.1836	.2772	.2920	.3442	.0181	.0185	.0293	.0268	.0220	.0665	.1864	.0604	.0536	.0181
25,000	.1485	.2111	.3093	.3254	.3908	.0219	.0224	.0358	.0323	.0267	.0827	.2027	.0729	.0650	.0219
30,000	.1689	.2350	.3360	.3530	.4261	.0256	.0261	.0420	.0375	.0312	.0952	.2154	.0848	.0757	.0255
35,000	.1872	.2559	.3584	.3760	.4559	.0294	.0297	.0480	.0426	.0356	.1072	.2257	.0961	.0858	.0290
40,000	.2040	.2740	.3774	.3954	.4816	.0329	.0332	.0537	.0476	.0399	.1189	.2342	.1069	.0955	.0324

(a) Transition at 23,300. Compressions .3716 and .3776.

(b) Transition at 23,370. Compressions .0755 and .0781.

(c) Transition at 12,430. Compressions .0736 and .1504.

ments in the overlapping range has been anticipated in the previous paper.

The five alkali metals were from my stock, known to be of high purity. It is the same stock as that used in previous measurements (6), and reference is made to former papers for the details of purification, etc. The caesium was freshly distilled from a glass capsule obtained from MacKay in 1937 and not opened until now. The distillation, which was slow at a minimum temperature, was necessary to remove the impurity of dissolved oxide. The details of the distillation were as in former work. For the present measurements the lithium was placed directly in the carboly container, with no sheath of indium or other intermediary between it and the carboly. Some misgivings were felt in doing this, because there had been previous evidence in the work to 100,000 that there might be chemical attack on the carboly. None appeared in the present range, however, and the results should have the advantage of greater accuracy because of the absence of any second material in the piezometer. It was necessary to use a protecting sheath for the other four alkalis, however. This was made necessary both by their mechanical softness and their chemical activity. The sheath could not be made of indium or of lead, since both of these form alloys. The softest metal which appeared feasible for the sheath was aluminum. The sheath was in the form of a double cup. The volume of the aluminum varied from 70 to 200 per cent of the alkali metal, depending on the compressibility of the metal. The various corrections, including that for the compressibility of the sheath, averaged 10 per cent of the total volume decrement.

There are previous measurements on all of these alkali metals for comparison. For lithium the volume decrement at 40,000 previously found was 0.201 against 0.204 found now. For sodium the previous decrement at 40,000 was 0.273, against 0.274 now. For potassium the respective figures are 0.375 and 0.377. For rubidium the figures are 0.431 and 0.395. This large discrepancy is doubtless the fault almost entirely of the previous measurements. These were based on measurements by the method of linear compressibility up to 12,000, a method entirely unsuitable for this material because of its excessive mechanical softness. Furthermore, the theoretical calculations of Bardeen (7) had indicated that the previous values for rubidium were out of line with what was to be expected in

the direction now found. The percentage discrepancy between the former and present measurements is greatest at the low pressure end of the range. For caesium the respective figures are 0.487 and 0.482. The new figure is to be preferred. The volume discontinuity at the transition of caesium at 23,300 kg/cm² formerly found agrees exactly with that now found.

The beryllium I owe to Professor John Chipman of M. I. T. It was said to be of 99.7 to 99.8 purity. For further particulars the paper describing the measurements to 100,000 should be consulted. There are previous measurements (8) of the compressibility of beryllium to 12,000. These give for the volume decrement at 10,000 0.0076 against 0.0094 now found. The new value is doubtless to be preferred, because of greater purity of the present specimen. However, it must be recognized that the absolute compressibility of beryllium is so low as to restrict the accuracy obtainable with the present apparatus.

The titanium was obtained from MacKay. It was said to be of 99 per cent purity, but was hard and brittle. It is not improbable that there is a very small transition in the neighborhood of 35,000. The values given in the table are smoothed across this. There are no previous measurements for comparison. Titanium is one of the least compressible substances measured with the present apparatus, with correspondingly smaller accuracy.

The zinc was single-crystal material obtained a number of years ago from Dr. A. W. Hanson at the University of Iowa and known to be of high purity. One of the objects of measuring zinc was to find whether the indium sheath exerts an effectively hydrostatic pressure on the specimen so that the resulting measurement is one of true volume compression, and not of some other combination of the elastic constants. Since the linear compressibility of zinc is 8 times as great in one direction as the other, this is a particularly favorable material to show the effect if it exists. Three specimens were made, one with the cleavage plane perpendicular to the axis of the carboly piezometer, one with it parallel, and one at 45°. The measurements did show a perceptible trace of the effect suspected, and in the expected direction. The volume compression on an arbitrary scale at the maximum pressure varied from 886 to 896. This is so very far from a factor of 8 to 1 that it is probably safe to assume that for most materials the stresses are sensibly hydro-

static. The figures given in the table are the average for the three orientations, and therefore possibly a trifle low. Previous measurements (9) have been made to 12,000 on the single crystal in different directions and the cubic compression calculated. The previous value at 10,000 so calculated was 0.0299 against 0.0294 found now.

The germanium I owe to the courtesy of Professor Lark-Horovitz. It has been measured to 100,000 and reference is made to that paper for further details. There are no other measurements. Over the range to 40,000 the relation between volume and pressure fails markedly of being a second-degree relation. The maximum deviation from linearity is at 12,000 instead of 20,000, and the change in direction in the general neighborhood of 12,000 is so abrupt as almost to constitute a transition of the second kind.

Zirconium was cut from a specimen obtained many years ago from Eindhoven used in previous measurements (10) to 12,000. The volume decrement formerly found at 10,000 was 0.0103 against 0.0111 found now. This is one of the more incompressible substances.

Lanthanum, cerium, praseodymium, and neodymium were all obtained from Mackay, all fresh material shipped under oil. The purity was not stated, but judging by the general appearance and mechanical softness the purity was high. Three of these metals have been measured previously (11) to 12,000 by the method of linear compressibility. The crystal system of cerium is cubic, and of the other three hexagonal close-packed. Except for cerium it was therefore not legitimate to calculate volume compression from linear compression, but in view of the close-packed character of the hexagonal structure the error was probably not large.

The compression previously found for lanthanum at 10,000 was 0.0339 against 0.0370 found now. The present value is to be preferred both because of the presumptively greater purity and also because lanthanum is not in the cubic system. The transition at 23,370 was not previously known; it runs cleanly with narrow region of indifference.

Cerium is anomalous in two respects; there is a large transition with 8 per cent volume change at 12,430, and below the transition the compressibility increases markedly with increasing pressure, the volume decrement at 10,000 being 17 per cent greater than would be given by linear extrapolation from 5,000. Previous measurements showed the same abnormal increase of compressibility,

and also a transition. The transition, however, was at a much lower pressure, 7,500 kg/cm². It was found to be sluggish and the change of volume was not determined, the measurements having been made on a piece of wire, not an advantageous form of specimen. The transition now found was sharp and rapid. The new values are without doubt greatly to be preferred; the difference may well be ascribed to inferior purity of the former sample. A still earlier exploration of a sample of cerium with still inferior purity had disclosed no transition at all. It is, however, surprising that the pressure of the transition is so sensitive to impurity. It would indicate that the impurity forms solid solutions, and probably with both phases and with different concentrations. The previous measurements of volume compression, by linear compression of wire, were made only to 4,000 in order to avoid the effect of the transition. Extrapolation to 5,000, assuming uniform compression in all directions, of the former measurements, gives 0.0269 against 0.0234 found now. The new value is to be preferred.

In view of the anomalies of both lanthanum and cerium, increasing from lanthanum to cerium, it was somewhat of a surprise that praseodymium, the next rare earth metal after cerium, shows no anomaly whatever, but the curve is perfectly smooth. Its volume compression at 10,000, previously found, was 0.0326 against 0.0328 found now.

The curve for neodymium is perfectly smooth. There are no previous values for comparison.

Minerals. I am indebted for eleven minerals to Professor Francis Birch, who selected them from the collections of the Harvard Geology Department. Professor Birch had them ground in his machine shop by Mr. Harold Ames to the shape required for the measurements. The truncated cone form was used, and indium was placed below the specimen, between it and the stationary piston, as well as on the sides of the cone and above it, in order to ensure as close an approach to true hydrostatic pressure as possible. The specimens were all single crystals. Two specimens of orthoclase were measured; one from Madagascar was clear, and the other from Spain was opaque with small black inclusions. The olivine was gem material (peridot) from St. John's Island, Red Sea, Egypt. The diopside was from De Kalk, N. Y. The grossularite, a variety of garnet, had the indicated composition $\text{Ca}_3\text{Al}_2(\text{SiO}_4)_3$. The "garnet" was from Connecticut, and the hypersthene from Labrador.

TABLE IV
COMPRESSION OF VARIOUS MINERALS

Pressure kg/cm ²	Quartz Crystal	Ortho- clase Mada- gascar	Labra- dorite	Calcite	Olivine	Diop- side	Grossu- larite	Garnet	Hyper- sthene	Ortho- clase Spain	Halite
0	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000
10,000	.0236	.0171	.0133	.0134 (a)	.0079	.0088	.0072	.0071	.0101	.0175	.0366
20,000	.0441	.0333	.0260	.0725	.0156	.0169	.0140	.0138	.0191	.0335	.0664
30,000	.0625	.0488	.0381	.0887	.0231	.0245	.0204	.0200	.0272	.0484	.0924
40,000	.0792	.0634	.0495	.1019	.0304	.0318	.0264	.0257	.0347	.0625	.1160

(a) Two transitions

The results are collected in Table IV. There are previous measurements for a number of the minerals. For quartz, former measurements (12) to 12,000 give for the volume decrement at 10,000 0.0242 against 0.0236 found now. Extrapolating by a second degree expression to 40,000 the former measurements give a volume decrement of 0.0696 against 0.0792 actually found now. The extrapolation gives considerably too small a decrement at the high pressures; this is the usual direction of discrepancy. The two orthoclases differ little in compressibility, in spite of the great difference in appearance. Former measurements (13) to 12,000 gave at 10,000 0.0195 against 0.0171 and 0.0175 found now. Labradorite has not been previously measured. Calcite has been previously measured (14) to 50,000; in those measurements the two transitions between 10,000 and 20,000 were more carefully studied than here. In the present work the two transitions were not resolved. The former decrements at 20,000 and 40,000 were 0.077 and 0.096 respectively against 0.073 and 0.102 found now. The present results differ from the former ones in giving a greater compressibility in the range between 20,000 and 40,000. Of the remaining minerals previous measurements have been made only for halite. Previous measurements gave for the decrement at 20,000 and 40,000 respectively 0.0664 and 0.1130 against 0.0664 and 0.1160 found now. The close agreement in the results for the two varieties of garnet is to be noticed.

Substances with Transitions. Most of these were substances previously investigated (16), for which the transition parameters have been determined. There are, however, a few new ones, the transitions of which were discovered in the course of this work. Five substances with newly discovered transitions are deferred for listing in Table VII. The particular point in investigating

these substances was to find the relative compressibilities of the two phases at the transition point. It had been previously found that in the majority of cases the high pressure phase, that is, the phase with the smaller volume, has the larger compressibility, a paradoxical result. The material was, in the case of those substances measured before, the same old stock, and reference is made to previous papers for a description of it. The few new materials will be described in due course. The results are shown in Table V.

The volume discontinuity of ammonium formate previously found was 0.0860 against 0.0860 found now. In general comment on the comparative volume decrements, the larger of two values is presumptively more accurate, the smaller value being due to incomplete running of the transition. This substance shows a drop in compressibility to approximately one half on passing from the low to the high pressure form.

Methylamine hydrochloride has two transitions, at approximately 5,000 and 25,000. The volume discontinuities previously found were $0.049 \pm$ and $0.012 \pm$ against 0.0520 and 0.0158 found now. There is no appreciable difference in compressibility of the two phases at 25,000. Not enough points were taken to determine the relative compressibility of the two low pressure phases. It is to be noted, however, that at low pressures the compressibility varies with pressure by an amount abnormally large for a solid.

The volume discontinuity of CsMnO_4 previously found was 0.0275 against 0.0241 now. At the transition pressure the high pressure form is approximately 11 per cent less compressible than the low pressure form.

Comparison of the present values for KCN with previous ones is not easy. It was previously found that KCN has at least four modifications. In order to obtain these, temperature was varied from dry ice temperature to 200° C. Most of the

TABLE V
SUBSTANCES WITH TRANSITIONS

Pressure kg/cm ²	Ammonium Formate	Methyl- amine Hydro- chloride	Cs Mn O ₄	K C N	Ag CN	PbI ₂	Cu ₂ I ₂	Urea	Thiourea
0	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000
5,000	.0386	.0397 (b)	.0270	.0280	.0466	.0332 (f)	.0133	.0375 (h)	.0619 (i)
10,000	.0670 (a)	.1186	.0497 (d)	.0539	.0787	.1014	.0247 (g)	.1328	.0922
15,000	.1940	.1406	.0938	.0777	.1041	.1203	.0717	.1563	.1162
20,000	.2052	.1601	.1099	.0996 (e)	.1251	.1359	.0844	.1759	.1352
25,000	.2157	.1779 (c)	.1246	.2030	.1433	.1491	.0958	.1925	.1511
30,000	.2255	.2099	.1384	.2166	.1594	.1604	.1064	.2066	.1650
35,000	.2348	.2251	.1516	.2287	.1741	.1712	.1164	.2188	.1776
40,000	.2438	.2398	.1644	.2402	.1879	.1810	.1260	.2295	.1893

- (a) Transition at 11,420; Volume decrements .0742 and .1853
 (b) Transition at 5,530; Volume decrements .0436 and .0956
 (c) Transition at 25,270; Volume decrements .1790 and .1948
 (d) Transition at 13,430; Volume decrements .0643 and .0884
 (e) Transition at 20,340; Volume decrements .1011 and .1885
 (f) Transition at 5,150; Volume decrements .0369 and .0761
 (g) Transition at 14,400; Volume decrements .0339 and .0702
 (h) Transition at 5,490; Volume decrements .0411 and .1053
 (i) Transition at 3,540; Volume decrements .0309 and .0512

TABLE V (Continued)
SUBSTANCES WITH TRANSITIONS

Pressure kg/cm ²	Nitrourea	Semi- carbamide Hydro- chloride	Quinone	Guan- idine Sulfate	d-Camphor	Ammonium Penta- borate	Potas- sium Penta- borate	Dextrose Sodium Iodide	MgSO ₄ ·7- H ₂ O
0	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000
5,000	.0354 (j)	.0276 (k)	.0611	.1757 (m)	.1365 (o)	.0360	.0754 (q)	.0263	.0235
10,000	.1156	.0525	.0997	.1951 (n)	.1712	.0606	.0977	.0494	.0445 (u)
15,000	.1383	.0708	.1300	.2161	.1962	.0806	.1171	.0697	.0844
20,000	.1570	.0864	.1552	.2284	.2158	.0984 (p)	.1337 (r)	.0880	.0999
25,000	.1725	.0998	.1763	.2388	.2319	.1378	.1549	.1045	.1139 (v)
30,000	.1861	.1119	.1943	.2480	.2456	.1529	.1666	.1196 (s)	.1539
35,000	.1981	.1229	.2095	.2565	.2577	.1646	.1767	.1489 (t)	.1644
40,000	.2088	.1332	.2224	.2647	.2694	.1741	.1858	.1693	.1747

- (j) Transition at 5,510; Volume decrements .0387 and .0911
 (k) Transition at 9,470; Volume decrements .0469 and .0501
 (l) Transition at 4,530; Volume decrements .0477 and .0568
 (m) Three transitions below 5,000.
 (n) Transition at 10,460; Volume decrements .1968 and .2027
 (o) Transition at 3,540; Volume decrements .0748 and .1229
 (p) Transition at 23,300; Volume decrements .1092 and .1317
 (q) Transition at 3,540; Volume decrements .0211 and .0663
 (r) Transition at 20,340; Volume decrements .1348 and .1411
 (s) Transition at 30,220; Volume decrements .1202 and .1364
 (t) Transition at 37,190; Volume decrements .1542 and .1622
 (u) Very sluggish transition between 10,000 and 15,000.
 (v) Probably two sluggish transitions in neighborhood of 25,000. Volume discontinuity of one about four times that of other.

transitions are fast, but at low pressures and high temperatures there is one transition so sluggish that it could not be brought down to room temperature, and furthermore there was evidence at the higher temperatures of the capricious appearance of an absolutely unstable form. The present measurements gave evidence only of the high pressure transition, in the neighborhood of 20,000. This ran unusually sharply, and all the measurements on this substance were unusually good, the difference between readings with increasing and decreasing pressure being unusually small. However, the volume change at the transition was now found considerably smaller than the previous value, 0.0874 against 0.102. The atmospheric density, calculated from the absolute position of the piston, was high, 1.64 against 1.52 given in I. C. T. It is perhaps not inconceivable that on the initial seasoning application of pressure a small amount of the absolutely unstable phase appeared and maintained itself. This is consistent with a larger than usual permanent change of volume after the seasoning application. The present results show a 23 per cent drop of compressibility on passing through the transition from the low to the high pressure form.

No evidence for a transition of AgCN was found in the present work. Previously a sluggish transition with very small volume change, 0.001, was found in the neighborhood of 14,000.

The volume discontinuity previously found for PbI_2 was larger than that found now, 0.049 against 0.039. The transition comes at such a low pressure that the change of compressibility on passing through the transition could not be established.

The former and the present transition parameters for Cu_2I_2 agree very closely; the pressures are indistinguishable and the volume discontinuity was 0.0360 against 0.0363 now. There is a 35 per cent increase of compressibility on passing through the transition to the high pressure phase. The transition of thiourea has been previously studied, but only at temperatures of 100° or above. Extrapolated to 25° the former measurements would give 3,460 for the transition pressure and 0.0139 for the discontinuity of volume against 3,540 and 0.0203 given above. The transition pressure is too low to permit a determination of the relative compressibility of the two phases.

Previous measurements on nitrourea disclosed no certain transition. However, the pressure exploration was combined with high temperatures and it appeared that there were complex

decomposition phenomena. It is probable that the transition was missed in the former work because of some irreversible transformation of the substance. In the present work a clean transition with 5 per cent volume change was found near 5,000. Any discontinuity of compressibility on passing through the transition is too small to be established.

In previous work on semicarbazide hydrochloride the measurements were confined to temperatures of 75° or higher because the transition was too sluggish at lower temperatures. In the present measurements at room temperature the transition was very sluggish, running at 15,400 with increasing pressure and 3,540 with decreasing pressure. Within these pressure limits the curves with increasing and decreasing pressure were parallel, indicating no appreciable difference of compressibility between the low and high pressure phases. The mean transition pressure of the present work, 9,470, is markedly higher than the 5,500 extrapolated from previous work. The extrapolated volume discontinuity is about ten times that given in the table. Comparison of measurements with so sluggish a transition is not significant.

The transition parameters obtained for quinone with the present apparatus are in much doubt, the transition limits being 4,000 kg/cm^2 wide. The former determinations were also in doubt, no determinations of volume discontinuity being attempted below 75° because of sluggishness of the transition. The former volume discontinuity extrapolated is 0.0370 against 0.0091 found now. Allowing maximum uncertainty to the extrapolation there would seem to be little doubt that the present volume discontinuity is too small. The present results give no sufficient evidence as to a discontinuity of compressibility at the transition.

Guanidine sulfate has three transitions below 5,000 which run so sluggishly that a slow change of volume continues for some time after pressure has been released and the apparatus disassembled. No attempt was made to resolve these transitions, but reference is made to the previous work. There is also a sluggish transition near 10,000 for which a volume discontinuity of 0.0059 was found in the present work against 0.0071 formerly. It seems probable, although not certain, that there is a moderate increase of compressibility on passing to the high pressure form through the transition at 10,000.

The transitions of d-camphor have been studied in two previous papers. The phase diagram is

the most complicated of any substance yet investigated, there being probably eleven modifications up to 35,000. A number of these are sluggish and run only at elevated temperatures. In the present work the complicated change which starts with modification II and ends with III, perhaps passing through IV and V as intermediate forms, was found to run at a mean pressure of 3,540 against 2,700 formerly. The present over-all change of volume is 0.048 against 0.053 formerly. The former work indicates by extrapolation that a transition from III to VIII should run at room temperature in the neighborhood of 13,000. No evidence for this was found in the present work, the transition apparently being totally suppressed by sluggishness at the low temperature. This means that the compression data given in the table above the transition pressure pertain to the modification III. The data would indicate a drop of compressibility to nearly one half on passing from II to III.

Ammonium perborate has not been previously measured. I owe it to the courtesy of Dr. Hans Jaffe of the Brush Development Co. It was provided in single crystal form, and had been produced as part of the war time program of investigation of all possible piezo-electric crystals. My intention was to measure it in my program of linear compressibility measurements up to 30,000. Discovery of transitions, however, made it impossible to use for this purpose. This substance in all probability has two transitions instead of the one shown in the table. Below 5,000 there is probably a small transition with volume discontinuity of the order of one seventh of that given in the table at higher pressures. Both transitions are sluggish. The volume discontinuity associated with the transition at 23,000 is probably too small and the compressibility immediately above the transition too high. The data as given in the table indicate a jump up of compressibility on passing to higher pressures through the transition, and an abnormally rapid dropping of the compressibility of the high pressure phase with increasing pressure.

Potassium pentaborate, like ammonium pentaborate, has not been previously measured. It was obtained from the same source, for the same purpose, and like it had to be discarded for measurement of the linear compressibility because of transitions. It also has two transitions, but inversely situated as compared with ammonium pentaborate. Here the larger transition is at the low pressure, and one with volume discontinuity

only one seventh as large at the high pressure. The sluggishness is not as great as for the ammonium salt. At the high pressure transition there is no appreciable discontinuity of compressibility. There may be a slight upward jump in compressibility on passing to the high pressure form at 3,540, although this is not certain.

Dextrose sodium iodide I owe to the courtesy of Dr. S. O. Morgan of the Bell Telephone Laboratories. It was single crystal stock, destined for measurement of the linear compressibility in the 30,000 apparatus. Two transitions were found, both above 30,000, so that it was possible to measure the linear compressibility over the entire range up to 30,000 in addition to the present measurements of volume compression to 40,000. Reference is made to a following paper for the details of the linear compressions in different directions. The volume compression at 30,000 calculated from the linear compressions was 0.1183 against 0.1196 found now.

The $\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$ I owe to the kindness of Mr. George C. Kennedey, who grew it from aqueous solution by the method of slowly lowering temperature. It was destined for measurements of the linear compression up to 30,000, but the discovery of the complicated system of transitions indicated in the table prevented measurements of linear compression above 10,000. At 10,000 the volume compression calculated from the linear compressions was 0.0408 against 0.0445 given in the table. It is probable that the lower value is more accurate, the present measurements being obscured by the sluggish transition.

Miscellaneous Compounds. Compounds 1 to 8 in Table VI were obtained from the Eastman Kodak Co., from their commercial stock. Of these numbers 1 to 5 were tried because they have multiple carbon bonds, and it was thought that there was some possibility that such compounds might suffer irreversible transitions at sufficiently high pressures similar to that found in CS_2 . None was found, however. I owe the suggestion of which compounds of this nature would be most feasible to try to Dr. Linus Pauling.

Compounds 9 to 25 were single crystal stock, destined to be used in the measurements of linear compression to 30,000. Full details about the origins of this material will be found in a paper to follow this. Comment here is required on only two of these materials. $\text{NiSO}_4 \cdot 6\text{H}_2\text{O}$ has a very marked transition of the second kind in the direction perpendicular to the axis in the neigh-

TABLE VI
VOLUME DECREMENTS OF MISCELLANEOUS COMPOUNDS

Pressure kg/cm ²	1 Melamine	2 Cyanamide	3 Di Cyanamide	4 Hexamethylenetetramine	5 Oxalic Acid anhydrous	6 2,4-Dichlorophenol	7 Iodoform	8 Urea Nitrate	9 Ammonium Phosphate	10 Potassium Phosphate	11 Sulfamic Acid	12 Li Na ₂ Cr ₂ O ₇ 6H ₂ O	13 NaCl O ₂
0	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000
5,000	.0376	.0357	.0340	.0433	.0357	.0549	.0549	.0372	.0177	.0179	.0207	.0172	.0185
10,000	.0618	.0615	.0589	.0739	.0620	.0893	.0921	.0642	.0332	.0335	.0378	.0345	.0349
15,000	.0811	.0832	.0796	.0976	.0835	.1149	.1194	.0855	.0471	.0474	.0524	.0490	.0491
20,000	.0975	.1019	.0976	.1167	.1010	.1358	.1414	.1034	.0595	.0599	.0654	.0620	.0616
25,000	.1116	.1184	.1138	.1330	.1161	.1533	.1599	.1191	.0709	.0713	.0775	.0753	.0736
30,000	.1242	.1334	.1285	.1474	.1296	.1687	.1759	.1331	.0815	.0817	.0885	.0853	.0854
35,000	.1358	.1471	.1421	.1599	.1421	.1823	.1902	.1456	.0914	.0912	.0970	.0935	.0952
40,000	.1469	.1600	.1547	.1708	.1538	.1945	.2034	.1569	.1006	.0996	.1050	.1033	.1031

TABLE VI (Continued)
VOLUME DECREMENTS OF MISCELLANEOUS COMPOUNDS

Pressure kg/cm ²	14 Rochelle Salt	15 Potassium Alum	16 Ni SO ₄ 6H ₂ O	17 Sodium Ammonium Tartrate	18 Rubidium Tartrate	19 Morpholine Hydrogen Tartrate	20 Ammonium hydrogen Phosphate	21 Ethylene Diamine Tartrate	22 Dextrose Sodium Chloride	23 HCO ₃	24 Benzil	25 Strontium Formate
0	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000
5,000	.0235	.0282	.0174	.0271	.0234	.0333	.0170	.0290	.0266	.0264	.0605	.0180
10,000	.0439	.0514	.0340	.0498	.0435	.0596	.0322	.0523	.0490	.0459	.0961	.0344
15,000	.0616	.0704	.0477	.0692	.0607	.0812	.0459	.0718	.0684	.0625	.1243	.0491
20,000	.0770	.0869	.0596	.0863	.0758	.0995	.0585	.0886	.0861	.0770	.1480	.0621
25,000	.0920	.1020	.0739	.1014	.0894	.1155	.0700	.1033	.1025	.0898	.1676	.0741
30,000	.1053	.1157	.0870	.1148	.1014	.1298	.0806	.1161	.1178	.1015	.1838	.0856
35,000	.1167	.1281	.0979	.1267	.1120	.1424	.0904	.1273	.1320	.1123	.1978	.0958
40,000	.1262	.1393	.1070	.1372	.1214	.1536	.0999	.1372	.1452	.1225	.2102	.1052

borhood of 20,000, the compressibility increasing abruptly at this pressure. The same anomaly is shown also by the volume measurements of Table VI, but quantitatively it is not nearly as large as would be demanded by the length measurements. It would appear that this anomaly does not become fully developed when the stress is not truly hydrostatic. The second material is benzil, which showed a complicated system of anomalies for the length measurements, but no trace of them in the volume measurements of Table VI. Again, part at least of the anomaly would seem to be suppressed by comparatively light constraint.

Compounds with Ortho-, Meta-, and Para- Forms. A study was made of a large number of compounds of this class to find whether there is any systematic variation in compressibility. The compounds were selected from the catalogue of the Eastman Kodak Co., all the groups for which the three forms were listed and for which all three are solid under ordinary conditions. The results are collected in Table VII. There are a few groups for which only two forms are tabulated; in these groups three forms had been listed and ordered but one of the forms proved to be out of stock. The purity is that usual to chemicals of this nature, and is indicated in the catalogue. In a few cases grades of "technical" or "practical" purity only were available; these are indicated in the following. As furnishing some clue to the character of the material, the densities at atmospheric pressure and room temperature are also recorded in the table. These densities were obtained incidentally in the course of the measurements from the weight and the absolute dimensions at atmospheric pressure of the charge when mounted in the piezometer.

The arrangement in the table is a sort of hybrid alphabetical arrangement, according to the most important part of the molecule.

Of the compounds, o- and m- amino phenol were listed as "practical" grade, and m-phenylene diamine as "technical." The m-chloroacetanilide was marked on the bottle "to contain 5 per cent of an aromatic amine"; the di-m-cresyl carbonate contained an appreciable quantity of some sort of moisture which squeezed out when the pellet for the piezometer was formed, and the tri-m-cresyl thiophosphate contained so much visible moisture that it did not seem worth while to measure it. It should be noticed incidentally that the para form of the sodium-xylene-sulfonate is not similar in structure to the other two,

TABLE VII
COMPRESSIONS OF ORTHO-, META-, AND PARA-COMPOUNDS

Pressure Kg./cm ²	1						2			3			4			5			6			7		
	Chloroacetanilide C ₈ H ₇ O ₂ NCI			Nitro-aniline C ₆ H ₄ O ₂ N ₂			Diphenyl Benzene C ₁₂ H ₁₀			Nitro-chloro- benzene C ₆ H ₄ O ₂ NCI			Nitro-bromo-benzene C ₆ H ₄ O ₂ NBr			Nitro-iodo-benzene C ₆ H ₄ O ₂ NI			Amino-Benzic Acid C ₇ H ₇ O ₂ N					
	o	m	p	o	m	p	o	m	p	o	p	o	m	p	o	m	p	o	m	p	o	m	p	
0	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	
2,500	.0347	.0311	.0259	.0228	.0240	.0255	.0339	.0294	.0314	.0333	.0328	.0320	.0253	.0266	.0310	.0268	.0271	.0265	.0160	.0271				
5,000	.0610	.0572	.0477	.0421	.0438	.0457	.0609	.0536	.0561	.0673	.0584	.0556	.0456	.0488	.0544	.0489	.0493	.0479	.0292	.0483				
10,000	.0998	.0971	.0822	.0729	.0748	.0772	.1012	.0918	.0934	.1113	.0963	.0991	.0774	.0843	.0893	.0825	.0835	.0814	.0503	.0808				
15,000	.1297	.1261	.1084	.0964	.0991	.1018	.1303	.1199	.1195	.1386	.1237	.1292	.1018	.1105	.1152	.1077	.1087	.1064	.0671	.1058				
20,000	.1540	.1490	.1292	.1149	.1190	.1217	.1526	.1414	.1394	.1591	.1455	.1513	.1214	.1312	.1355	.1276	.1290	.1267	.0809	.1262				
25,000	.1740	.1678	.1463	.1305	.1357	.1385	.1708	.1591	.1557	.1752	.1633	.1687	.1377	.1487	.1522	.1438	.1460	.1433	.0928	.1431				
30,000	.1901	.1852	.1603	.1439	.1498	.1532	.1856	.1739	.1698	.1890	.1785	.1833	.1517	.1638	.1664	.1577	.1607	.1573	.1034	.1578				
35,000	.2034	.1960	.1714	.1559	.1620	.1662	.1982	.1865	.1823	.2005	.1916	.1956	.1637	.1770	.1797	.1699	.1733	.1691	.1130	.1707				
40,000	.2144	.2066	.1803	.1669	.1733	.1777	.2091	.1973	.1937	.2107	.2031	.2061	.1741	.1887	.1916	.1811	.1846	.1793	.1221	.1821				
Atmospheric Density	1.349	1.337	1.335	1.465	1.434	1.446	1.171	1.195	1.247	1.558	1.512	1.943	1.982	1.952	2.304	2.171	2.198	1.346	1.526	1.371				

(a) Transition at 4,030. Compressions .0484 and .0550.

(b) Transition at 7,490. Compressions .0741 and .0795.

TABLE VII (Continued)
COMPRESSIONS OF ORTHO-, META-, AND PARA-COMPOUNDS

Pressure kg/cm ²	8			9			10			11			12			13			14		
	Chloro-Benzonic Acid C ₇ H ₅ O ₂ Cl			Bromo-Benzonic Acid C ₇ H ₄ O ₂ Br			Iodo-Benzonic Acid C ₇ H ₃ O ₂ I			Methyl- α -Nitro- cinamate C ₁₀ H ₉ O ₄ N			Di- α -cresyl carbonate C ₁₄ H ₁₄ O ₃			Amino Phenol C ₆ H ₇ ON			Nitro-Phenol C ₆ H ₅ O ₂ N		
	o	m	p	o	m	p	o	m	p	o	m	p	o	m	p	o	m	p	o	m	p
0	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000
2,500	.0273	.0288	.0273	.0266	.0308	.0263	.0275	.0266	.0257	.0301	.0292	.0273	.0365	.0340	.0312	.0267	.0239	.0236	.0317	.0258	.0271
5,000	.0694	.0734	.0694	.0812	.0914	.0804	.0824	.0834	.0819	.0887	.0855	.0836	.0623	.0606	.0553	.0467	.0429	.0423	.0563	.0462	.0488
10,000	.0829	.0862	.0832	.0812	.0914	.0804	.0824	.0834	.0819	.0887	.0855	.0836	.0623	.0606	.0553	.0467	.0429	.0423	.0563	.0462	.0488
15,000	.0884	.0924	.0884	.0861	.0961	.0853	.0871	.0881	.0866	.0934	.0902	.0883	.0676	.0659	.0606	.0519	.0481	.0475	.0616	.0515	.0541
20,000	.0928	.0968	.0928	.0905	.1005	.0897	.0915	.0925	.0910	.0978	.0946	.0927	.0706	.0689	.0636	.0549	.0511	.0505	.0646	.0545	.0571
25,000	.0983	.1023	.0983	.0960	.1060	.0952	.0970	.0980	.0965	.1033	.1001	.0982	.0751	.0734	.0681	.0594	.0556	.0550	.0691	.0590	.0616
30,000	.1028	.1068	.1028	.1005	.1105	.1000	.1018	.1028	.1013	.1081	.1049	.1030	.0800	.0783	.0730	.0643	.0605	.0600	.0740	.0639	.0665
35,000	.1083	.1123	.1083	.1060	.1160	.1055	.1073	.1083	.1068	.1136	.1104	.1085	.0854	.0837	.0784	.0697	.0659	.0655	.0795	.0694	.0720
40,000	.1138	.1178	.1138	.1115	.1215	.1110	.1128	.1138	.1123	.1191	.1159	.1140	.0903	.0886	.0833	.0746	.0708	.0705	.0848	.0747	.0773
Atmospheric Density	1.530	1.516	1.511	1.916	1.840	1.871	2.211	2.138	2.173	1.401	1.396	1.416	1.243	1.284	1.265	1.279	1.255	1.287	1.481	1.476	1.468

TABLE VII (Continued)

COMPRESSIONS OF ORTHO-, META-, AND PARA-COMPOUNDS

Pressure kg/cm ²	15			16			17			18			19			20			21			22		
	Phenylene-diamine C ₆ H ₄ N ₂			Phenylene-diamine Hydrochloride C ₆ H ₄ N ₂ Cl			Amino Benzene Sulfonic Acid C ₆ H ₄ ONS			Sodium- α -Xylene Sulfonate C ₁₀ H ₈ ONa			Tri- α - Cresyl Thio- phosphate C ₂₁ H ₂₇ O ₃ P			Toluic Acid C ₇ H ₅ O ₂			Acetyl- α - Toluidine C ₉ H ₉ ON			Toluidine Hydrochloride C ₇ H ₉ ONCl		
	o	m	p	o	m	p	o	m	p	o	m	p	o	m	p	o	m	p	o	m	p	o	m	p
0	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000
2,500	.0255	.0253	.0267	.0183	.0227	.0153	.0221	.0188	.0197	.0206	.0236	.0195	.0320	.0364	.0329	.0305	.0328	.0284	.0324	.0280	.0329	.0328	.0329	.0329
5,000	.0468	.0465	.0482	.0340	.0403	.0281	.0402	.0323	.0358	.0391	.0440	.0354	.0563	.0643	.0583	.0539	.0588	.0519	.0582	.0503	.0416	.0588	.0774	(e)
10,000	.0809	.0797	.0811	.0601	.0673	.0493	.0633	.0523	.0558	.0706	.0775	.0609	.0929	.1041	.0945	.0896	.0975	.0874	.0935	.0843	.0684	.0976	.1073	
15,000	.1070	.1053	.1061	.0835	.0893	.0669	.0838	.0676	.0706	.0939	.1029	.0814	.1196	.1333	.1216	.1168	.1255	.1134	.1308	.1097	.0899	.1261	.1388	
20,000	.1279	.1253	.1257	.1030	.1080	.0824	.1076	.0908	.0938	.1165	.1229	.0987	.1410	.1558	.1430	.1387	.1473	.1341	.1550	.1298	.1075	.1458	.1460	
25,000	.1450	.1412	.1417	.1237	.1246	.0959	.1223	.0902	.0936	.1342	.1390	.1137	.1587	.1741	.1609	.1567	.1664	.1509	.1743	.1458	.1226	.1688	.1698	
30,000	.1596	.1544	.1555	.1399	.1394	.1079	.1356	.0997	.0988	.1492	.1524	.1261	.1739	.1895	.1763	.1725	.1825	.1653	.1899	.1599	.1359	.1807	.1807	
35,000	.1720	.1656	.1675	.1536	.1523	.1186	.1473	.1087	.1079	.1617	.1638	.1369	.1874	.2025	.1900	.1861	.1962	.1783	.2032	.1722	.1479	.1946	.1861	
40,000	.1825	.1756	.1779	.1648	.1634	.1284	.1578	.1172	.1172	.1722	.1737	.1467	.1998	.2137	.2023	.1976	.2079	.1897	.2147	.1829	.1587	.2065	.1972	
Atmospheric Density	1.229	1.223	1.259	1.424	1.378	1.493	1.617	1.668	1.478	1.476	1.492	1.498	1.293	1.419	1.309	1.232	1.296	1.162	1.138	1.169	1.247	1.216	1.191	

(c) Transition at 3.980. Compressions .0270 and .0376.

(d) Transition at 11.440. Compressions .1058 and .1082.

(e) Transition at 2.550. Compressions .0234 and .0551.

but contains one molecule of water of crystallization.

There is a great range in the mechanical properties of these compounds, and these properties might well be studied for their own sake. Most of the compounds form smooth and compact pellets when subjected to the preliminary pressure of the order of 15,000 kg/cm², but there are a few exceptions in which the pellet is extremely friable and difficult to handle. Notably in this class were the three sodium-xylene-sulfonates. The pellet in these cases can be made coherent enough to get into the piezometer by greasing the mold in which it is formed with a minimum amount of a mixture of vaseline and colloidal graphite. Sometimes merely rubbing the internal wall of the steel mold with graphite was sufficient.

In general the mechanical strength of these compounds is so low that one can expect the effect of the initial configuration, whether as powder or flakes or granules, to vanish from the final measurements, which should give very closely the true cubic compression of single crystal material under hydrostatic pressure. Direct check was made of this for o-chloro benzoic acid, which showed no significant difference between a pellet formed by fusing and turning to shape and a pellet formed in the regular way by compression of the dry powder.

Certain features of the behavior of various of the substances require detailed comment. There is an increase of compressibility of about 30 per cent on passing through the transition of o-nitrobenzene from the low to the high pressure form. There is an increase of compressibility of 65 per cent on passing from the low to the high pressure form of o-nitrochlorobenzene, and the compressibility of the latter form decreases abnormally rapidly with increasing pressure immediately above the transition point. There is an enormous increase of compressibility on passing to the high pressure form at the low pressure transition of p-amino-benzene sulfonic acid, the exact magnitude of which is difficult to estimate because of the low pressure range of stability of the low form. The second form drops rapidly in compressibility with increasing pressure above the transition. At the second transition the compressibility also jumps up on passing to the high pressure form. This substance is one which exhibited extreme friability and friction in the formation of the pellet; there may well have been a connection with the low pressure transition. The transition listed for p-toluidine hydrochloride was unusually

sluggish and ran perceptibly over a pressure range of 20,000 kg/cm² with increasing pressure, and the reverse transition with decreasing pressure required an unusually long time for completion at atmospheric pressure. The compressions in the first 20,000 kg/cm² cannot be expected to be very accurate, but may be expected to be obscured by transition effects. The data given in the table for o-phenylene diamine hydrochloride are smoothed so as to completely ignore a small initial episode at low pressures in some respects like a transition, but largely irreversible. It is also to be noticed that the compressibility of this substance decreases linearly with pressure above 20,000, instead of at a continually retarded rate, as for most all other substances in the table. Finally, m-phenylene-diamine was the only substance which during compression exhibited any effects indicative of friction or failure of approximate hydrostatic pressure. This snapped twice audibly on increase of pressure, and at one point there was a slight discontinuity in piston displacement. The behavior on release of pressure was normal. This material is unusually glass-like and brittle.

In order to give a general idea of the nature of the results for these compounds, the compressions at the top pressure, 40,000, are plotted in Figure 1 for the different members of the various series of compounds, including in the compressions the transitions in the five cases in which they occur. It is evident at a glance that there is no systematic effect of the o-, m-, p- structure on compression, although there are many instances where the differences of compression between the different forms are large. Statistically, the ortho form is the most compressible of the three in 9 cases, and least compressible in 6; the meta form is most compressible in 6 and least compressible in 8 cases; and the para form most compressible in 7 and least compressible in 8 cases. Considering the small number of examples this distribution must be judged to be completely random. The abnormally small compression of the meta forms of amino-benzoic acid and amino-benzene sulfonic acid is to be commented on. In view of the very large variations in these two series it must be recognized that on occasion other factors than o-, m-, or p- position may be much more potent in determining compressibility. It would be rewarding to make an X-ray analysis of these two amino compounds to find whether there is anything unusual about the crystal structure.

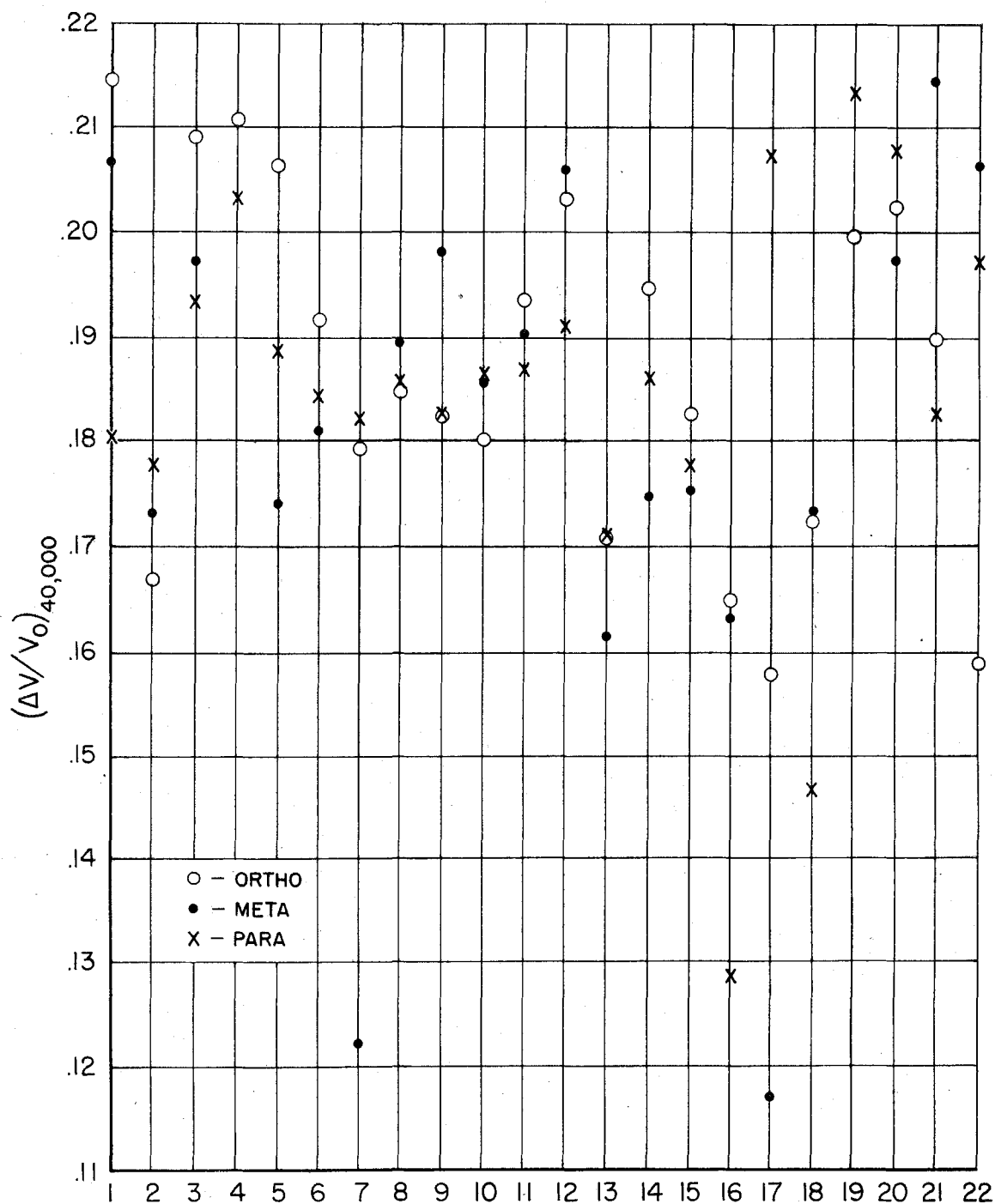


FIGURE 1. The relative compressions at 40,000 kg/cm² of the various series of o-, m-, and p- compounds as numbered in Table VII.

Other things being equal, it is to be expected that the compressions in any single series of compounds will be in the inverse order of the densities at atmospheric pressure. In order to see to what extent the density controls, I have compared the order of the inverse compressions with that of the atmospheric densities for all 22 series of compounds, and find the same order for the two properties in only 5 of the 22 instances. This is hardly more than would be expected by pure chance, so that the conclusion may be drawn that the connection is not immediate and unique between density and compression. There is however, a recognizable statistical connection. If one plots the product of atmospheric density and relative compression at 40,000 instead of merely relative compression at 40,000 in a diagram analogous to figure 1, it will be found that the three points for any one series have an obvious tendency to bunch much more closely than in figure 1.

It might perhaps be expected that at pressures as high as 40,000 any specific effects of structure might tend to be wiped out, leaving outstanding the contribution to the compression of the atoms themselves. In this case, one might expect some approach to an additive law of compression in terms of atomic constitution. In order to facilitate examination of this question the gross overall atomic formulas of the various compounds have been given in Table VII. I have not, however, been able to find any significant correlation, suggesting the conclusion that the intrinsic compressibility of the atoms entering into these compounds differs so little that any effect of them is obscured by other factors. It might be mentioned, however, that the two series differing only by the substitution of one halogen for another, namely the series 4, 5, 6 and 8, 9, 10 of the table, do show the same progression of values in the product of atmospheric density and compression

at 40,000, a progression not shown by the compressions themselves. The variation of the product within any single series is, furthermore, comparatively minor.

The shape of the curves of volume decrement against pressure is in general the same for the three members of a series. There are, however, several examples of crossing of the curves, which means a different variation of compressibility with pressure for the different forms. Among the most pronounced of these instances are: m- and p- diphenyl benzene, o- and p- phenylene diamine, and o- and m- phenylene diamine hydrochloride. The apparent example of o- and m- dicresyl carbonate is uncertain, because of probable impurity of the m- form, a perceptible amount of liquid having been squeezed out on formation of the pellet.

REFERENCES

1. P. W. Bridgman, Proc. Amer. Acad. 76, 9-24, 1945.
2. P. W. Bridgman, Proc. Amer. Acad. 63, 409, 1929.
3. E. B. Dane, Jr. and Francis Birch, Jour. App. Phys, 9, 669-674, 1938.
4. P. W. Bridgman, Amer. Jour. Sci. 237, 13, 1939.
5. P. W. Bridgman, Amer. Jour. Sci. 7 (5), 100, 1924.
6. P. W. Bridgman, Proc. Amer. Acad. 58, 166-242, 1923; 60, 385-421, 1925; 70, 71-101, 1935; 72, 207-225, 1938; Phys. Rev. 27, 68-86, 1926; 60, 351-354, 1941.
7. J. Bardeen, Jour. Chem. Phys. 6, 372-378, 1938.
8. P. W. Bridgman, Proc. Amer. Acad. 68, 49, 1933.
9. P. W. Bridgman, Phys. Rev. 47, 393-397, 1935.
10. P. W. Bridgman, Proc. Amer. Acad. 63, 348, 1928.
11. P. W. Bridgman, Proc. Amer. Acad. 62, 207-226, 1927.
12. P. W. Bridgman, Amer. Jour. Sci. 10, 491, 1925.
13. P. W. Bridgman, Amer. Jour. Sci. 15, 294, 1928.
14. Reference 4, p. 8.
15. P. W. Bridgman, Proc. Amer. Acad. 74, 31, 1940.
16. P. W. Bridgman, Proc. Amer. Acad. 72, 46-136, 227-267, 1937.

Proceedings of the American Academy of Arts and Sciences

VOL. 76, No. 4, P. 89-157—OCTOBER, 1948

THE LINEAR COMPRESSION OF VARIOUS SINGLE CRYSTALS
TO 30,000 kg/cm²

By P. W. BRIDGMAN

THE SCATTERING OF HIGH VELOCITY NEUTRAL PARTICLES. I.

By I. AMDUR, C. F. GLICK AND H. PEARLMAN

RECORDS OF MEETINGS
FROM OCTOBER 1944 TO MAY 1948

Proceedings of the American Academy of Arts and Sciences

VOL. 76, No. 4, P. 89-99—OCTOBER, 1948

THE LINEAR COMPRESSION OF VARIOUS SINGLE CRYSTALS
TO 30,000 kg/cm²

By P. W. BRIDGMAN

INVESTIGATIONS OF LIGHT AND HEAT MADE AND PUBLISHED WITH AID OF THE
RUMFORD FUND

THE LINEAR COMPRESSION OF VARIOUS SINGLE CRYSTALS TO 30,000 kg/cm²

By P. W. BRIDGMAN

Received Oct., 1947.

CONTENTS

INTRODUCTION.....	89
APPARATUS AND METHOD.....	89
DETAILED DATA.....	91
Magnesium.....	91
Ammonium Dihydrogen Phosphate.....	91
Primary Potassium Phosphate.....	92
LiNa ₃ Cr ₂ O ₇ ·6H ₂ O.....	92
Rubidium Tartrate.....	92
Dextrose Sodium Chloride.....	92
Dextrose Sodium Iodide.....	93
NiSO ₄ ·6H ₂ O.....	93
Benzil.....	95
Sodium Ammonium Tartrate.....	96
Strontium Formate.....	96
Sulfamic Acid.....	96
HIO ₃	96
MgSO ₄ ·7H ₂ O.....	96
Morpholine Hydrogen Tartrate.....	97
Rochelle Salts.....	97
DISCUSSION.....	98

INTRODUCTION

During the war a number of laboratories were actively engaged in searching for crystals capable of replacing quartz or rochelle salts for various purposes of transmission or reception, and in this search large programs of crystal growing were carried out. Some of the crystals made in this way were large enough to permit measurements of linear compression, and I was fortunate enough to obtain a number for this purpose. The results on these and one other, magnesium, form the subject of this paper. The crystals investigated here were all such that their distortion under hydrostatic pressure is completely determined if the change of linear dimensions is known in three or fewer orthogonal directions. That is, no monoclinic or triclinic crystals were investigated, although a number of these had been grown for piezo-electrical purposes and were available. Neither were any cubic crystals investigated, such not having piezo-electric properties.

Before undertaking the measurements a pre-

liminary investigation of the substance was made in the apparatus¹ for rapid determination of cubic compressibility to 40,000 to find whether there were any polymorphic transitions in the contemplated range, since measurements of linear compressibility in general have no significance when carried through a transition point. Among the available substances several were found with polymorphic transitions below 30,000. In general no attempt was made to measure the linear compressions of these. The data for their volume compressions will be found in the previous paper describing the measurements with the 40,000 apparatus. One of the substances with a transition, MgSO₄·7H₂O, was however measured in the low pressure range below its first transition.

APPARATUS AND METHOD

The method used in this work was that of the "lever piezometer," in which the change of dimensions of the specimen is magnified with a lever which moves a wire carrying a current over a contact fixed to the apparatus, the amount of motion being determined by potentiometer measurements of the resistance between a contact fixed to the wire and the contact over which it slides. This method has been extensively employed hitherto² up to 12,000 kg/cm², and is the most accurate and sensitive method for the determination of the compression of solids used to date. Its use to 30,000 in the present work is new. The particular point in making the measurements over the wider range is the greater accuracy with which it is possible to determine the changes of compressibility with pressure, knowledge of which is important for the theory of the solid state. Eventually it is intended to measure a large number of substances with similar apparatus over this range; such measurements will form a useful supplement to other less accurate measurements over wider ranges. The particular crystals of this paper are well adapted for the first measurements in this range because their compressibilities are so high that certain irregularities which still persist in the apparatus

are without appreciable effect. Measurements by this method and in this range cannot yet be advantageously made on substances as incompressible as iron, but this part of the program must wait for further improvements, which are already well under way.

Because of the emphasis on precision and the higher order terms it is necessary to take greater care with the measurement of pressure than is adequate, for instance, in the measurements to 100,000. It is now necessary to know the deviation of the manganin gauge from linearity. It has already been established³ that this deviation is so slight that a calibration at two pressure fixed points is sufficient. The gauges were calibrated by the transition of bismuth and the freezing of mercury at room temperature, the data for which are known. The calibration must be made anew for every individual manganin coil, of which two were used in this work.

The lever piezometer had to be specially designed and constructed. It is somewhat smaller than formerly, being required to fit a hole 0.50 instead of 0.62 inches in diameter. Furthermore, a different method of assembly had to be designed so that the insulating plug at the bottom of the cylinder need not be removed for every new set-up, the assembly of this plug being much more time consuming in the 30,000 apparatus than with the former 12,000 apparatus. Mr. L. H. Abbot successfully designed an arrangement of spring clips which permitted the piezometer with specimen in place to be inserted as a single unit into the pressure cylinder from the moving plug end, this plug being naturally removed after every release of pressure. Various calibrations have to be made on the piezometer for the magnification of the lever, the resistance of the wire and its pressure coefficient etc. These calibrations were not essentially different from those previously necessary to 12,000 and need not be described further in detail.

Various minor improvements in the technique of handling the 30,000 apparatus have been effected. Some of these, having to do with methods of assembling the insulating plug and the packing ring for it, have already been described in the previous paper⁴ giving new results to 100,000. I now have in all three complete equipments for reaching 30,000. These are somewhat individual in the difficulties which they present. The one in which the present measurements were made has perhaps given the most trouble. An especial trouble with this,

not shown by the others, although the construction is identical as far as is evident, has been that the moving piston has a strong tendency to seize on the walls of the cylinder, resulting in abnormally high friction and also leak. This difficulty has been overcome by giving a proper hardness to the moving packing rings and by lightly copper plating before every run the steel parts which move over each other. In addition to these difficulties the most disastrous explosion yet experienced with any 30,000 apparatus occurred during this work. In the design used in the early measurements the insulating plug, where it projects from the pressure cylinder, was without external support for a distance of perhaps 5/16 inch on a diameter of 9/16 inch. There was some plastic swelling of this unsupported part, and in the course of the work this part had been refired several times by removing altogether a few thousandths of an inch from the diameter. The failure consisted in a complete collapse at the maximum pressure of the unsupported protruding part. This failed by shear on an angle much blunter than 45°, releasing the contents of the cylinder, which were completely destroyed. Evidently the plastic flow in the protruding part, which was of Rockwell C hardness 59, had proceeded beyond the limit of tolerance. The new design was made with only half as long a protruding part, and to date no further difficulty has occurred.

The methods of calculation in the following were like those previously used in the lower range, and need not be further described. The results are essentially differential results with respect to American Ingot iron, the absolute compressibility of which has already been established⁵ over this range by a different method. By making calibrating runs with iron, taking the difference between the calibrating run and the actual run and using in the calculation the known absolute value for iron, the absolute changes of dimension in the various crystallographically independent directions could be eventually obtained and tabulated. From the linear changes of dimensions the change of volume was then calculated. In this calculation five place logarithms had to be used, four places being sufficient for the linear changes. Finally, the relative lengths and volumes were calculated from the changes, and recorded in the tables given here.

In the following a rough measure is given of the order of accuracy by recording the average deviation of a single experimental point from a

smooth curve in terms of the percentage of the differential change of dimensions at the highest pressure. The calculations involved first determining at every pressure what the displacement would have been if the relation with pressure had been linear passing through the top point, then plotting the deviation from linearity as a function of pressure, and finally passing a smooth curve through the deviation points. The sum of the deviations from this smooth curve of all the points was obtained by addition with the dividers, and this sum was divided by the total number of observations and the displacement at the maximum to get the average percentage deviation above. In the usual routine, 17 readings uniformly scattered over the entire range were made in addition to an initial seasoning application of 10,000. The 17 readings were made with increasing and decreasing pressure, the decreasing readings being staggered between the increasing readings. The "probable" error of the result tabulated is of course much less than the irregularity of a single reading, perhaps something of the order of one quarter of it for a total of 17 readings, neglecting any systematic error. Furthermore, this error is on the differential compressibility; the absolute compressibility is more accurate by an amount depending on the difference between the substance in question and iron.

DETAILED DATA

The detailed presentation of data now follows. The substances are given first for which measurements in two directions were sufficient and then those which demanded three. In each section the order is, with two exceptions, the order of increasing volume compression at 30,000. The results are given in tables, length and volume at 2,500, 5,000, and then at 5,000 intervals to 30,000. No attempt has been made to find a universal formula which would cover all the data. A second degree expression such as was usually adequate in the former range up to 12,000 is definitely not adequate in most of the cases, although frequently the failure is by a small amount. Most of the substances in the following are conventional enough in their behavior. Only two have markedly unusual features: $\text{NiSO}_4 \cdot 6\text{H}_2\text{O}$, which has a very marked transition of the second kind in one direction, and benzil, which has a more complicated anomaly.

Magnesium. This metal is included here with other dissimilar substances because its absolute compressibility is high enough to permit accept-

able measurements with the present apparatus. The material was from the same crystal as that previously measured⁶ to 12,000. The results are given in Table I. For the parallel direction the

TABLE I
MAGNESIUM

Pressure kg/cm ²	Length		Volume
	⊥ hex. axis	|| hex. axis	
0	1.00000	1.00000	1.00000
2,500	.99775	.99770	.99320
5,000	.99553	.99542	.98657
10,000	.99122	.99100	.97366
15,000	.98716	.98683	.96166
20,000	.98322	.98280	.95010
25,000	.97954	.97904	.93938
30,000	.97612	.97548	.92944

mean deviation of a single reading from a smooth curve was 0.17 per cent, and for the perpendicular direction 0.22 per cent. Compared with previous results the changes of length at 10,000 found now are about 3 per cent less than those formerly found. The curvature or deviation from linearity in the parallel direction is not greatly different from that found before. The curvature in the perpendicular direction, on the other hand, is now materially less than before. The curvature previously found in the perpendicular direction was 50 per cent greater than that in the parallel direction, whereas now the two curvatures are equal within 1 per cent. The compressions in the two directions now found are very nearly equal, as would be expected from the crystal structure of magnesium, a hexagonal close packed structure of *spheres*. The compression found now is about 0.5 per cent greater in the direction parallel to the hexagonal axis than at right angles.

Ammonium Dihydrogen Phosphate ("A.D.P."). This I owe to the kindness of Dr. Hans Jaffe of the Brush Development Co., the results are shown in Table II. It will be noticed that the

TABLE II
AMMONIUM DIHYDROGEN PHOSPHATE

Pressure kg/cm ²	Length		Volume
	|| optic axis	⊥ optic axis	
0	1.00000	1.00000	1.00000
2,500	.99542	.99795	.99135
5,000	.99104	.99604	.98322
10,000	.98267	.99253	.96405
15,000	.97511	.98944	.95462
20,000	.96818	.98663	.94247
25,000	.96170	.98389	.93097
30,000	.95557	.98142	.92042

compression is somewhat twice as great parallel to the optic axis as at right angles. The mean deviations of single readings from smooth curves were 0.12 per cent for the parallel direction and 0.65 per cent perpendicular. The greater irregularity perpendicular to the axis corresponds to the smaller compressibility.

Primary Potassium Phosphate ("P.K."). The material was furnished by Dr. Jaffe.

The results are shown in Table III. In the

TABLE III
PRIMARY POTASSIUM PHOSPHATE

Pressure kg/cm ²	Length		Volume
	"a" direction	"c" direction	
0	1.00000	1.00000	1.00000
2,500	.99688	.99734	.99112
5,000	.99405	.99475	.98295
10,000	.98896	.98976	.96802
15,000	.98440	.98487	.95438
20,000	.98018	.98033	.94182
25,000	.97649	.97604	.93068
30,000	.97291	.97212	.92015

"a" direction the average deviation of a single reading from a smooth curve was 0.41 per cent, and in the "c" direction 0.47 per cent. Compared with ammonium dihydrogen phosphate the overall cubic compression is very nearly the same, but the linear compression does not follow the same pattern, being very nearly the same for the two directions for P.K., whereas there was a difference by a factor of two for A.D.P. There seem to be no previous measurements on either of these materials for comparison.

LiNa₃Cr₂O₇·6H₂O. This material I owe to the kindness of Dr. S. O. Morgan of the Bell Telephone Laboratories.

The results are shown in Table IV. The com-

TABLE IV
LiNa₃Cr₂O₇·6H₂O

Pressure kg/cm ²	Length		Volume
	x direction	z direction	
0	1.00000	1.00000	1.00000
2,500	.99696	.99698	.99095
5,000	.99400	.99446	.98256
10,000	.98832	.98975	.96676
15,000	.98300	.98540	.95216
20,000	.97804	.98144	.93882
25,000	.97315	.97786	.92604
30,000	.96849	.97446	.91400

pression in the z direction is about 20 per cent less than at right angles. The mean deviation of a single reading from a smooth curve was 0.18

per cent for the x direction, and 0.25 per cent for z. There are no previously published measurements for comparison. The 40,000 apparatus gave for the volume decrement at 30,000 0.0885 against 0.0860 calculated above.

Rubidium Tartrate. The material was supplied by Dr. Morgan.

The results are given in Table V. The com-

TABLE V
RUBIDIUM TARTRATE

Pressure kg/cm ²	Length		Volume
	x direction	z direction	
0	1.00000	1.00000	1.00000
2,500	.99569	.99821	.98965
5,000	.99151	.99671	.97985
10,000	.98362	.99389	.96162
15,000	.97656	.99144	.94552
20,000	.96992	.98949	.93090
25,000	.96390	.98776	.91772
30,000	.95858	.98625	.90624

pressibility in the z direction is only one third as great as at right angles. The mean deviation of a single reading from a smooth curve was 0.25 per cent for the x direction, and 0.6 per cent for z. The only previous measurements for comparison are those of the volume decrement with the 40,000 apparatus. This apparatus gave for the volume decrement at 30,000 0.1014, against 0.0938 above from the linear compressions. The discrepancy is larger than usual.

Dextrose Sodium Chloride. The material was supplied by Dr. Morgan.

The results are given in Table VI. The com-

TABLE VI
DEXTROSE SODIUM CHLORIDE

Pressure kg/cm ²	Length		Volume
	x direction	z direction	
0	1.00000	1.00000	1.00000
2,500	.99494	.99714	.98710
5,000	.98972	.99445	.97410
10,000	.98028	.98911	.95048
15,000	.97339	.98427	.93260
20,000	.96648	.98000	.91540
25,000	.96037	.97557	.89974
30,000	.95443	.97172	.88516

pressibility in the z direction is roughly one half that at right angles. In the z direction there is an abnormal episode between 17,000 and 25,000, the compressibility dropping with pressure at an abnormally high rate at the beginning of the interval. Since all the experimental points consistently indicated the same thing it seems

probable that the abnormality is real, and it was therefore not smoothed out in the table. This abnormality does not seem to fall under the conventional classifications as transition of the second or higher order.

The mean deviation of a single reading from a smooth curve was 0.73 per cent in the x direction and 0.26 in z . The only previous measurements for comparison are with the 40,000 apparatus. This gave for the volume decrement at 30,000 0.1178 against 0.1148 above.

Dextrose Sodium Iodide. The material was furnished by Dr. Morgan.

The results are given in Table VII. The

TABLE VII
DEXTROSE SODIUM IODIDE

Pressure kg/cm ²	Length		Volume
	x direction	z direction	
0	1.00000	1.00000	1.00000
2,500	.99478	.99612	.98576
5,000	.99008	.99240	.97282
10,000	.98172	.98532	.94964
15,000	.97434	.97865	.92907
20,000	.96791	.97293	.91146
25,000	.96194	.96767	.89544
30,000	.95692	.96286	.88166

average deviation of a single reading from a smooth curve was 0.08 per cent for the x direction and 0.24 for z . The volume decrement given by the 40,000 apparatus at 30,000 was 0.1196 against 0.1183 above. It is to be noticed that the compressibilities in the two directions are much more nearly equal for dextrose sodium iodide than they are for the corresponding chloride. The volume decrement of the iodide is greater by a small amount. A difference in this direction would be expected on general grounds as a result of replacing chlorine with iodine.

NiSO₄·6H₂O. This was supplied by Dr. Morgan.

The behavior in the z direction up to 30,000 proved to be entirely normal. In the direction at right angles, however, there is a very marked anomaly in the neighborhood of 20,000, as shown in Figure 1. Below 20,000 the length decreases nearly linearly with pressure with a mean compressibility only about 40 per cent of that in the z direction. Near 20,000 there is a very rapid increase of compressibility in a narrow pressure interval, the maximum compressibility attained being approximately 20 fold the original. Between 20,000 and 30,000 the relation between length in the x direction and pressure is very far

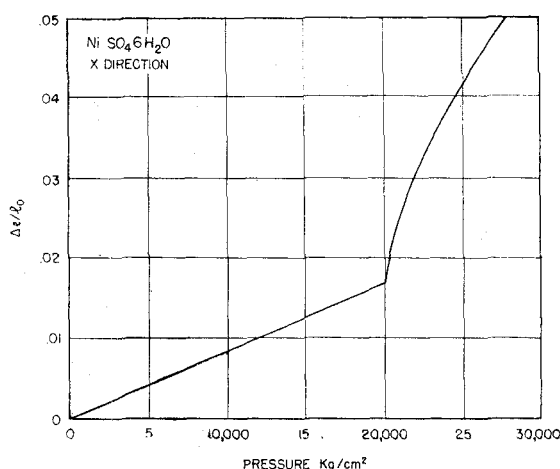


FIGURE 1. The relative change of length perpendicular to the axis of $\text{NiSO}_4 \cdot 6\text{H}_2\text{O}$ as a function of pressure.

from linear, the compressibility at 30,000 having dropped to approximately one third that at 20,000.

Four different set-ups with four different specimens were made in the x direction. Two of the specimens were cut at right angles to each other, both in the plane perpendicular to z , in order to check whether any triaxiality developed above the transition point. No evidence for this was found. The behavior of these four samples differed slightly and beyond the errors of measurement. The pressure of discontinuity was 19,320, 19,700, 20,000 and 20,050 for the four specimens respectively. The maximum difference in the changes of length was about 2 per cent. The results given in the table are a rough average for the four directions, taking the pressure of discontinuity as 20,000 and throwing the most weight above the transition on the one specimen which was taken up to the full 30,000.

If pressure readings are taken close together in the region of the anomaly the sharp discontinuity disappears, and there appears only a region of very rapidly varying curvature. In Figure 2 the fine detail is shown in the neighborhood of the anomaly. The points in this diagram were taken with decreasing pressure after the full 30,000 had been reached. This excursion to the maximum produced an irreversible permanent fractional change of length when 20,000 was recovered of 0.0004.

The final results, with the fine detail in the region of anomaly smoothed over, are shown in Table VIII. In the z direction the average

TABLE VIII
NiSO₄·6H₂O

Pressure kg/cm ²	Length		Volume
	x direction	z direction	
0	1.00000	1.00000	1.00000
2,500	.99828	.99491	.99148
5,000	.99661	.99014	.98345
10,000	.99331	.98104	.96796
15,000	.99005	.97291	.95365
20,000	.98685	.96575	.94050
22,500	.97216	.96263	.90978
25,000	.96284	.95991	.88990
27,500	.95653	.95738	.87594
30,000	.95122	.95511	.86420

deviation of a single reading from a smooth curve was 0.15 per cent, and in the perpendicular direction (best of the four runs and below the anomaly) was 0.46 per cent.

As usual, the preliminary examination was made in the 40,000 apparatus, and an accelerated increase of compressibility found in the neighborhood of 20,000. However, this had none of the abruptness of the change of linear dimensions. The change of volume at 30,000 given by the 40,000 apparatus was 0.0870 against 0.1358 above. The magnitude of the discrepancy is quite without precedent, and is impossible to explain by error. The effect must be real, and it must mean that whatever it is that occurs at 20,000 is to a great extent suppressed under the constraints imposed in the 40,000 apparatus, in which pressure fails to be hydrostatic by several hundred kilograms under the best conditions, and by much more under unfavorable conditions of high rigidity in the specimen and large difference of compressibility in different directions. The lat-

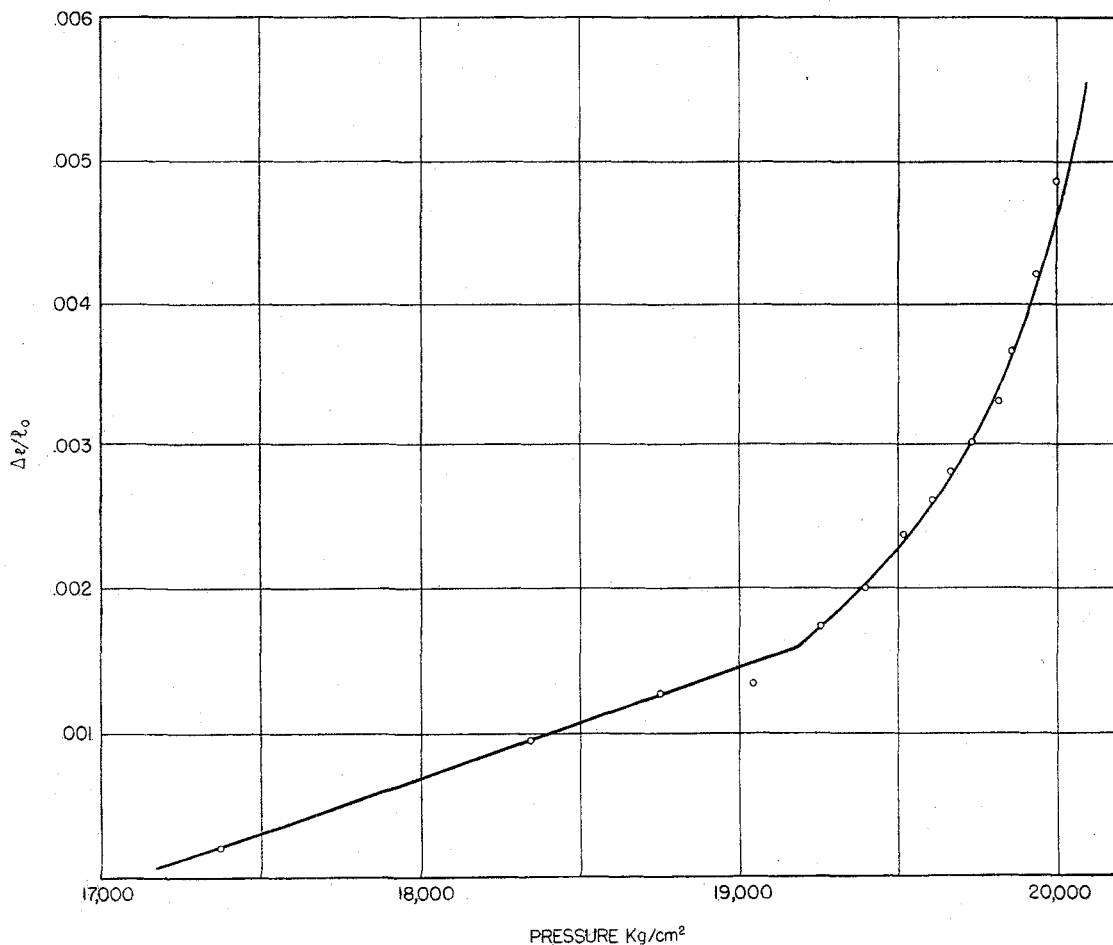


FIGURE 2. Plot on a much enlarged scale of the neighborhood of the break in Figure 1, together with the experimental points obtained with decreasing pressure.

ter condition, at least, is fulfilled by the present substance.

Benzil. I owe this to the kind offices of Lt. Paul H. Egli, through whom the Naval Research Laboratory supplied it to me. The orientations were kindly identified by Professor C. Frondel of the Department of Mineralogy of Harvard University.

Both directions are anomalous, and furthermore the anomalies are not connected in the way demanded by thermodynamics if the stress system is a pure hydrostatic pressure. The explanation does not appear, but must be connected in some way with a slight failure of the stress to be hydrostatic. The specimen in the piezometer, in order to be sure that all contacts shall be tight and there shall be no back lash, is subjected to a unidirectional compressional stress along the axis in addition to the hydrostatic pressure. This stress is of the order of only 0.5 kg/cm². Never before has there been any evidence that this stress plays any role.

Two specimens were used in each direction, and the anomalies repeated. The mean deviation of a single point from a smooth curve was 0.24 per cent for the "a" direction and 0.25 per cent for "c". The anomaly in the c direction consists in an abrupt increase of length at 22,500. From here the curve follows along parallel to its course before the jump, but on a higher level, until 26,800, when there is an abrupt downward turn in direction, but no discontinuity, until at 28,500 a rough prolongation of the original curve is reached. Pressure was not carried beyond this point. On release of pressure the course with increase of pressure was reversibly retraced. The experimental points are shown in Figure 3. Thermodynamics, of course, permits only transitions with decrease of volume, so that in the "a" direction this anomaly would demand a discontinuous decrease of length large enough to at least compensate for the increase at right angles. However, no anomaly whatever was found in the "a" direction at 22,500. There is a smaller repeatable and reversible anomaly at 12,500, which consists in a cusp-like increase of compressibility, or at least cusp-like to pressure readings spaced about 2,000 kg/cm² apart. This is followed by an inverse anomaly at 25,000, the compressibility becoming discontinuously smaller. This latter anomaly was reversible, but it was not checked by repetition with the second specimen, which was made so long in order to give greater

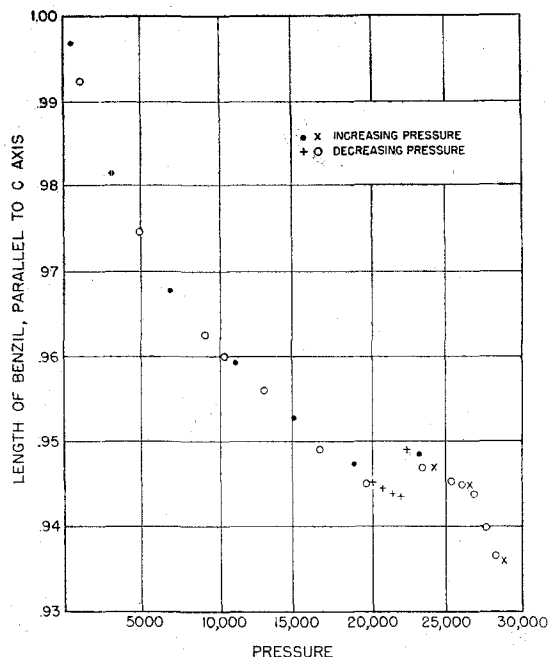


FIGURE 3. The relative change of length perpendicular to the axis of benzil as a function of pressure. The increase of length between 20,000 and 25,000 is reversible.

sensitiveness that it could not be carried above 25,000 without running beyond the stroke of the lever.

These anomalies are reproduced as they were found in Table IX. It would be misleading to

TABLE IX
BENZIL

Pressure kg/cm ²	Length	
	a direction	c direction
0	1.0000	1.0000
2,500	.9905	.9832
5,000	.9833	.9731
7,500	.9766	
10,000	.9705	.9598
12,500	.9650	
15,000	.9569	.9513
17,500	.9500	
20,000	.9438	.9446
22,500	.9379	.9418
		.9470
25,000	.9321	.9440
26,800		.9423
27,500	.9299	
28,500		.9345
30,000	.9269	

calculate from the changes of length the volume change, and this column is therefore omitted.

Preliminary measurements were made as usual

in the 40,000 apparatus, and no anomalies found at all. The change of volume at 30,000 found with it was 0.184, which is not far from what would be computed by taking the changes of length in Table IX at their face value.

Sodium Ammonium Tartrate. The material was furnished by Dr. Morgan.

The measurements went smoothly and without episode. Two complete sets of measurements were made on this substance with six specimens in all. The repetition was made necessary by a confusion of orientations in the first set by which two "*y*" orientations were measured and no *x*. On the repetition the agreement in the changes of length was exact for the *y* orientation and within 1 per cent for *z*. The results shown in Table X are those of the second set. The mean

TABLE X
SODIUM AMMONIUM TARTRATE

Pressure kg/cm ²	Length			Volume
	<i>x</i> direction	<i>y</i> direction	<i>z</i> direction	
0	1.00000	1.00000	1.00000	1.00000
2,500	.99332	.99752	.99622	.98712
5,000	.98693	.99523	.99263	.97498
10,000	.97556	.99108	.98612	.95342
15,000	.96575	.98739	.97994	.93444
20,000	.95701	.98403	.97468	.91788
25,000	.94907	.98082	.96993	.90288
30,000	.94284	.97784	.96564	.89028

deviations of single readings from smooth curves for the *x*, *y*, and *z* directions respectively were: 0.23, 0.43, and 0.27 per cent. The volume decrement at 30,000 obtained with the 40,000 apparatus was 0.1148 against 0.1097 above.

Strontium Formate. The material was supplied by the Naval Research Laboratory, and the identification of orientations made by Professor Fronzel.

The results are shown in Table XI. The average deviations of single readings from smooth

TABLE XI
STRONTIUM FORMATE

Pressure kg/cm ²	Length			Volume
	<i>a</i> direction	<i>b</i> direction	<i>c</i> direction	
0	1.00000	1.00000	1.00000	1.00000
2,500	.99670	.99802	.99617	.99092
5,000	.99390	.99610	.99271	.98278
10,000	.98870	.99236	.98629	.96770
15,000	.98387	.98886	.98024	.95368
20,000	.97932	.98566	.97452	.94068
25,000	.97516	.98260	.96923	.92870
30,000	.97143	.97965	.96426	.91764

curves in the *a*, *b*, and *c* directions were 0.42, 1.5, and 0.33 per cent respectively. The volume decrement at 30,000 found with the 40,000 apparatus was 0.0858 against 0.0824 above.

Sulfamic Acid. The material was supplied by Dr. Jaffe, who identified the axis. The system of axes adopted is that of Jaeger as quoted by Bryant.⁷ "According to this system the *b* axis coincides with the acute bisectrix. The *c* axis coincides with the normal to the optic plane."

TABLE XII
SULFAMIC ACID

Pressure kg/cm ²	Length			Volume
	<i>a</i> direction	<i>b</i> direction	<i>c</i> direction	
0	1.00000	1.00000	1.00000	1.00000
2,500	.99698	.99682	.99592	.98978
5,000	.99433	.99402	.99195	.98046
10,000	.98948	.98898	.98495	.96385
15,000	.98513	.98432	.97863	.94896
20,000	.98114	.98007	.97295	.93558
25,000	.97748	.97633	.96827	.92406
30,000	.97419	.97306	.96386	.91370

The results are shown in Table XII. The average deviations of single readings from smooth curves in the *a*, *b*, and *c* directions were 0.42, 0.36, and 0.36 per cent respectively. The volume decrement at 30,000 found with the 40,000 apparatus was 0.0885 against 0.0863 above.

HIO₃. The material was supplied by the Naval Research Laboratory and the identification of directions made by Professor Fronzel.

TABLE XIII
HIO₃

Pressure kg/cm ²	Length			Volume
	<i>a</i> direction	<i>b</i> direction	<i>c</i> direction	
0	1.00000	1.00000	1.00000	1.00000
2,500	.99789	.99481	.99625	.98900
5,000	.99592	.98995	.99276	.97880
10,000	.99229	.98106	.98688	.96070
15,000	.98894	.97349	.98034	.94382
20,000	.98588	.96680	.97510	.92942
25,000	.98316	.96059	.97020	.91534
30,000	.98068	.95549	.96560	.90482

The results are shown in Table XIII. The average deviations of single readings from smooth curves in the *a*, *b*, and *c* directions were 0.62, 0.24, and 0.62 per cent respectively. The volume decrement at 30,000 obtained with the 40,000 apparatus was 0.1015 against 0.0952 above.

MgSO₄·H₂O. This material I owe to the kindness of Mr. George C. Kennedey, who grew the crystals especially for these measurements from

aqueous solution by the method of slowly lowering the temperature. The work was done at Harvard University. During the war Mr. Kennedy had been engaged on similar work for the Navy.

Preliminary exploration with the 40,000 apparatus disclosed three transitions, one between 10,000 and 15,000, and two close together and not completely resolved in the neighborhood of 25,000. All these transitions are sluggish, with a wide region of indifference. The present measurements were of necessity restricted to pressures below 10,000. Even in this range the results were more irregular than usual.

TABLE XIV
MgSO₄·7H₂O

Pressure kg/cm ²	Length			Volume
	a direction	b direction	c direction	
0	1.00000	1.00000	1.00000	1.00000
2,500	.99666	.99563	.99649	.98880
5,000	.99348	.99131	.99341	.97834
7,500	.99042	.98705	.99070	.96850
10,000	.98750	.98286	.98826	.95918

The results are shown in Table XIV. The average deviation of a single reading from a smooth curve was 1.1, 0.75, and 1.2 per cent respectively for the *a*, *b*, and *c* directions. The change of volume at 10,000 found with the 40,000 apparatus was 0.0445 against 0.0408 above. The discrepancy is largely due to uncertainty in the 40,000 measurements due to sluggishness of the transitions.

Morpholine Hydrogen Tartrate. The material was supplied by Dr. Morgan.

TABLE XV
MORPHOLINE HYDROGEN TARTRATE

Pressure kg/cm ²	Length			Volume
	x direction	y direction	z direction	
0	1.00000	1.00000	1.00000	1.00000
2,500	.99191	.99786	.99346	.98324
5,000	.98521	.99585	.98378	.96516
10,000	.97345	.99203	.97202	.93866
15,000	.96402	.98856	.96289	.91764
20,000	.95573	.98532	.95555	.89982
25,000	.94850	.98229	.94888	.88408
30,000	.94191	.97954	.94384	.87080

The results are shown in Table XV. The mean deviation of a single reading from a smooth curve for the *x*, *y*, and *z*, directions respectively was 0.10, 0.46 and 0.15 per cent. The volume decrement at 30,000 found with the 40,000 apparatus was 0.1228 against 0.1292 above. The measure-

ments with this material went smoothly in all respects with a minimum of the irregularities which some of the other materials show. I think that many of these irregularities are not instrumental, but are genuinely associated with the materials.

Rochelle Salts. The material was supplied by Dr. Jaffe. Two completely independent sets of measurements were made with material from two different crystals. On the first determination there was apparently a confusion with regard to the "*b*" orientation, this apparently having been replaced by the *a* orientation. Repetition of the results was therefore demanded. Dr. Jaffe kindly provided a second batch of material with orientations marked, and Professor Fronzel made an independent confirmation of the orientations.

TABLE XVI
ROCHELLE SALTS

Pressure kg/cm ²	Length			Volume
	a direction	b direction	c direction	
0	1.00000	1.00000	1.00000	1.00000
2,500	.99382	.99743	.99613	.98742
5,000	.98789	.99505	.99260	.97570
10,000	.97773	.99043	.98626	.95504
15,000	.96868	.98628	.98079	.93704
20,000	.96032	.98270	.97588	.92096
25,000	.95270	.97975	.97151	.90684
30,000	.94597	.97722	.96728	.89420

The results for the second specimen are shown in Table XVI. The decrements of length in the *a* and *c* directions given by the first specimen agreed within about one per cent with the corresponding values for the second. The mean deviations of a single reading from a smooth curve for the *a*, *b*, and *c*, directions were respectively 0.28, 1.23, and 0.42 per cent respectively.

The confirmation of the results in Table XVI by the volume decrements measured independently with the 40,000 apparatus was closer than usual. The volume decrement at 30,000 given by the latter was 0.1053 against 0.1058 of the table. In addition to this, comparison may be made with my own former measurements³ of the change of length up to 12,000 kg/cm². The decrements of length at 10,000 kg/cm² formerly found in the *a*, *b*, and *c* directions respectively were 0.01029, 0.02217, and 0.01320 against 0.02227, 0.00957, and 0.01374 now given in Table XVI. It would appear that *a* and *b* orientations in the former work must have been

inverted, a probability which is strengthened by inspection of the original note books.

There seem to be no other measurements under hydrostatic pressure for comparison. There have, however, been a number of measurements of the elastic constants at atmospheric pressure from which the initial compressibilities may be computed. A summary of these may be found in Cady's book on Piezoelectricity. It would appear from an inspection of this work that none of the measurements of elastic constants are accurate enough to allow computations of the linear compressibilities of any reliability. In this calculation the errors conspire in a particularly unfavorable way. For instance, the linear compressibility in the *b* direction calculated with that combination of constants which is recommended as best turns out to be negative, a conclusion which can be rejected with confidence on the basis of the direct measurements. In general, the error in measuring the linear compressibilities appears to be much less than that in measuring the other constants, so that in calculating the other constants adjustments should be made so that they will yield the measured linear compressibilities.

DISCUSSION

This discussion will be concerned with several purely formal matters with the object of giving a better descriptive grasp of the results, and will not attempt at all to assess their physical significance.

In the first place, the magnitude of the mean compression is of interest. As a measure of this we may take the volume decrement under 30,000. Omitting the only metal in the above list, magnesium, and confining attention to the salts, the smallest volume decrement is for Ammonium Dihydrogen Phosphate, 0.0796, and the largest for $\text{NiSO}_4 \cdot 6\text{H}_2\text{O}$, 0.1358. This is variation by less than a factor of two, which is comparatively small in view of the known variation by a factor of 300 between the least and most compressible elements, carbon and caesium. In speculating on the reason for this it is to be remembered that all the substances measured here have this in common, that they are soluble in water and were grown in single crystal form from aqueous solution.

The degree of anisotropy of the crystal with regard to hydrostatic compression is of interest. This may be arbitrarily defined as the ratio of the decrement of linear dimension in the direction in which it is greatest to that in the direction in

TABLE XVII
SUMMARY

Substance	|| axis, c, or z			⊥ axis, a, or x			⊥ axis, b, or y			Volume			Anisotropy	
	$\left(\frac{\Delta l}{l_0}\right)_{30,000}$	Devia- tion	Relative Devia- tion	$\left(\frac{\Delta l}{l_0}\right)_{30,000}$	Devia- tion	Relative Devia- tion	$\left(\frac{\Delta l}{l_0}\right)_{30,000}$	Devia- tion	Relative Devia- tion	$\left(\frac{\Delta V}{V_0}\right)_{30,000}$	Devia- tion	Relative Devia- tion	Magni- tude	Axes of greatest and least compression
Magnesium	.02452	.0370	1.51	.02388	.0377	1.58				.07056	.0435	0.62	1.026	c, a
Ammonium Dihydrogen Phosphate	.04443	.0603	1.36	.01858	.0684	3.68				.07958	.0702	0.88	2.39	c, a
Primary Potassium Phosphate	.02788	.0427	1.53	.02709	.0761	2.81				.07985	.0714	0.89	1.027	c, a
$\text{LiNa}_2\text{Cr}_2\text{O}_6 \cdot 6\text{H}_2\text{O}$	.02554	.0717	2.80	.03151	.0397	1.26				.08600	.0563	0.65	1.234	a, c
Rubidium Tartrate	.01375	.1084	7.89	.04142	.0659	1.59				.09376	.0811	0.86	3.01	a, c
Dextrose Sodium Chloride	.02828	.0562	1.99	.04557	.0840	1.84				.11484	.0867	0.76	1.61	a, c
Dextrose Sodium Iodide	.03714	.0748	2.01	.04308	.0957	2.22				.11834	.0993	0.84	1.163	a, c
$\text{NiSO}_4 \cdot 6\text{H}_2\text{O}$	.04489	.1035	2.30	.04878	-.296	-6.07				-.159	-.159	-1.17	1.086	a, c
Sodium Ammonium Tartrate	.03436	.0837	2.43	.05716	.0992	1.73				.10972	.0977	0.89	2.58	a, b
Strontium Formate	.03574	.0528	1.48	.02857	.0648	2.27				.08236	.0624	0.76	1.755	c, b
Sulfamic Acid	.03614	.0913	2.52	.02581	.0763	2.95				.08630	.0914	1.06	1.40	c, a
HfO_3	.03440	.0716	2.08	.01932	.0725	3.75				.09518	.0902	0.95	2.30	b, a
Morpholine Hydrogen Tartrate	.05616	.1606	2.85	.05809	.1193	2.05				.12920	.1374	1.06	2.84	a, b
Rochelle Salts	.03272	.0865	2.64	.05403	.0797	1.47				.10580	.0998	0.94	2.37	a, b

which it is least. This is shown in Table XVII. Among the crystals with rotational symmetry requiring two constants, three are more compressible along the axis, and four at right angles. The anisotropy varies from 3.01 for rubidium tartrate to 1.029 for Primary Potassium Phosphate and 1.026 for magnesium. Among the orthorhombic crystals requiring three constants three are most compressible along the c axis, two along a and one along b . The anisotropy in this group varies from 2.84 for morpholine hydrogen tartrate to 1.398 for sulfamic acid. The anisotropy shown by this group of crystals is not large when it is considered that zinc is eight times more compressible along the axis than at right angles, and tellurium has a negative ratio in the two directions.

We next consider the deviations from linearity, or the curvature in the relation between pressure and distortion. This may be arbitrarily defined as the ratio of the difference between the actual distortion at 15,000 and the distortion which would have occurred at 15,000 if the relation were linear up to 30,000, to the distortion at 30,000. Expressed analytically for change of length, this is:

$$\text{Deviation} = \frac{\Delta l_{15,000} - \frac{1}{2}\Delta l_{30,000}}{\Delta l_{30,000}}$$

Previous experience would lead to the expectation that the "deviation" so defined would be larger the larger the absolute value of the distortion, or that deviation divided by the decrement of length at 30,000 would be roughly of the order of magnitude of unity and would not vary greatly from substance to substance. I have already shown that when the volume change up to 12,000 kg/cm² is represented by the two constant formula $\Delta V/V_0 = -ap + bp^2$, the dimensionless combination b/a^2 varies in the general neighborhood of unity.

In Table XVII are given the changes of dimensions at 30,000, the deviations, and the ratio of the deviation to the change at 30,000.

This latter we may define as the "relative deviation." The deviation varies from a maximum of 0.161 for morpholine hydrogen tartrate to a minimum among the salts of 0.0397 for $\text{LiNa}_3\text{Cr}_2\text{O}_7 \cdot 6\text{H}_2\text{O}$ and 0.0372 for magnesium. No correlation is obvious between deviation and direction in the crystal. The relative deviation, omitting for the moment rubidium tartrate, varies from 3.75 to 1.36 for changes of length and from 1.06 to 0.616 for changes of volume. The expectation is borne out that the relative deviation fluctuates in the general neighborhood of unity. Its range of fluctuation is definitely less than the range of fluctuation of the deviation itself, but the difference is not overwhelming. The deviation for the volume is in general not far from the deviation for the length, which means that the relative deviation for the volume is of the order of one third the relative deviation for length. There seems no general correlation between the relative deviation and direction.

Rubidium Tartrate is clearly an exception. Along the axis the compressibility is by far the least of any substance in the table, whereas at the same time its deviation from linearity is among the highest and its relative deviation is entirely out of line, being 7.89 against a next nearest figure 3.75. One might be tempted to suspect an approach to a transition of the second kind, but as a matter of fact the abnormally high curvature is distributed uniformly over the whole pressure range.

REFERENCES

- ¹ P. W. Bridgman, Reference to be supplied when preceding paper receives its designation.
- ² P. W. Bridgman, see, for example, Chapter VI in *The Physics of High Pressure*, G. Bell and Sons, London, 1931.
- ³ P. W. Bridgman, *Proc. Amer. Acad.* 74, 1-10, 1940.
- ⁴ P. W. Bridgman, *Proc. Amer. Acad.* Reference to be supplied. First paper of this series.
- ⁵ P. W. Bridgman, *Proc. Amer. Acad.* 74, 11-20, 1940.
- ⁶ P. W. Bridgman, *Proc. Amer. Acad.* 67, 29-41, 1932.
- ⁷ Bryant, *Jour. Amer. Chem. Soc.* 61, 2551, 1939.
- ⁸ P. W. Bridgman, *Proc. Amer. Acad.* 64, 67, 1928.

Proceedings of the American Academy of Arts and Sciences

VOL. 76, No. 4, P. 101-119—OCTOBER, 1948

THE SCATTERING OF HIGH VELOCITY NEUTRAL PARTICLES. I.

BY I. AMDUR, C. F. GLICK AND H. PEARLMAN

(Contribution from the Department of Chemistry, Massachusetts Institute of Technology,
Cambridge, Massachusetts)

THE SCATTERING OF HIGH VELOCITY NEUTRAL PARTICLES. I.

By I. AMDUR, C. F. GLICK,* AND H. PEARLMAN†

Received June 29, 1948

TABLE OF CONTENTS

A. INTRODUCTION.....	101
B. PREVIOUS CONTRIBUTIONS.....	102
C. PRESENT CONTRIBUTION.....	102
1. Structural Details of the Apparatus.....	103
2. Performance Characteristics of the Ap- paratus.....	109
a. Detector Characteristics.....	109
b. Arc Characteristics.....	110
c. Pirani Gage Characteristics.....	113
d. Scattering Section Pressure Char- acteristics.....	114
e. Preliminary Scattering Results.....	116
D. SUMMARY.....	118
E. ACKNOWLEDGMENTS.....	119

A. INTRODUCTION

The estimation of the interaction energies between atoms and molecules as functions of their separation distances is of fundamental importance for a complete understanding of numerous chemical and physical problems. Among the many properties which can be calculated from theory if the mutual energy of interaction is known are: compressibility and thermal expansion of solids and liquids, and transport properties (viscosity, thermal conductivity, and diffusion coefficients) of gases. To date, much of the information on intermolecular interactions has been derived from experimental measurements of these properties and their temperature coefficients. The results have not been completely satisfactory, however, for several reasons. First, the existence of intermolecular forces results, in some cases, in producing perturbations of the properties of an ideal system of forceless molecules, as, for example, the pressure-volume-temperature relations of a mass of a gas. When this

perturbation is not very large, it is very difficult to estimate interaction potentials from experimental measurements with satisfactory accuracy. Second, the theoretical treatment of the experimentally measured property is often so complicated that drastic simplification of the molecular model must be made before it is possible to obtain numerical values for the interaction potential. As a result, the conclusions often bear little resemblance to reality, as in the case of molecular models of mass points possessing only repulsive forces which are frequently assumed in order to deduce interaction potentials from experimental values of the coefficients of viscosity, thermal conductivity, and diffusion of gases at relatively low temperatures. Finally, the limited temperature range over which it is possible to make measurements results, in many cases, in values of the mutual potential energy which are valid over very narrow ranges of the separation distance.

A more direct approach to the experimental determination of intermolecular interactions would seem to lie in attempts to study actual collisions between molecules. If the masses, initial speeds, final speeds, and direction of scattering are known for a colliding system, it is possible to determine the potential energy of interaction at the distance of closest approach of the two particles.¹ This method of attack has the advantage that the effects of molecular interactions are not reflected in small changes in compressibility, viscosity, or similar properties characteristic of large aggregates of molecules, but directly in the change in speed and direction of the interacting molecules. As a consequence, the results of scattering experiments tend to lead directly to the desired information about molecular interactions. However, the experimental difficulties are great since well defined, unidirec-

* Present address, Barrett Division, Allied Chemical and Dye Corporation, Philadelphia, Pennsylvania.

† Present address, North American Aviation, Inc., Los Angeles, California.

¹ E. H. Kennard, *Kinetic Theory of Gases* (McGraw-Hill Book Company, Inc., New York, 1938), pp. 115-134.

tional beams of collision free neutral particles and accurate methods for detecting such beams are required. The discovery of Dunoyer² that thermal velocity molecular beams could be produced by methods similar to those used in collimating light showed that an experimental study of the physical characteristics of single collisions was plausible. The techniques of the molecular beam method were brilliantly developed by Stern and his co-workers³ between 1923 and 1933 so that the thermal velocity beam is now a well established, accurate research tool.

The scattering of molecular beams with ordinary thermal velocities provides information concerning intermolecular forces at relatively large separation distances where forces of attraction usually predominate over forces of repulsion.⁴ Scattering experiments of this type are of secondary interest to the authors for two reasons. First, other types of measurements already mentioned, although less satisfactory, are capable of supplying information in the same general range of interaction distances. Second, quantum theory calculations have been reasonably successful in predicting the magnitude of attractive forces, particularly for non-polar molecules. On the other hand, at small separation distances where repulsive forces predominate, theoretical calculations are not generally successful or possible and laboratory experiments on large aggregates of molecules are not feasible since temperatures are required in excess of the limit obtainable. Since the scattering of neutral particles with controlled high velocities appears to offer a unique approach to the study of repulsive interaction forces at small distances, the authors have endeavored to develop apparatus and techniques of the same high quality as those used in ordinary thermal velocity beam research.

B. PREVIOUS CONTRIBUTIONS

Beams of fast neutral atoms were first produced by Oliphant,⁵ who found a beam of neutral,

metastable ³S helium atoms while studying beams of helium ions. Beeck⁶ produced a beam of fast argon atoms by the process of "umladung" which involves the collision of an accelerated ion with a slow atom and results in a transfer of kinetic energy to yield a fast neutral atom and a slow ion. This method was further investigated by Kallman and his co-workers,⁷ and later used by Rostagni⁸ to produce beams of fast hydrogen, argon and neon.

Amdur and Pearlman,⁹ using a device similar to the proton source of Lamar and Luhr,¹⁰ introduced the use of high velocity neutral beams for the determination of repulsive intermolecular potentials from measured total collision cross-sections. They scattered fast hydrogen atoms in room temperature hydrogen gas and fast helium atoms in room temperature helium gas and were able to evaluate interaction potentials from their results. For the system, H—H₂¹¹, the repulsive potential energy may be expressed as

$$V(r) = 0.846 \times 10^{-10} \exp(-24.9r^2) + 0.211 \times 10^{-10} \exp(-2.40r^2) \text{ erg} \quad (1)$$

for values of r , the distance between mass points representing the hydrogen atom and the hydrogen molecule, in the range 0.28–0.70Å. The corresponding relation for the system He—He¹² is

$$V(r) = 11.3 \times 10^{-10} \exp(-4.63r^3) \text{ erg} \quad (2)$$

for values of r in the range 0.55–1.05Å.

C. PRESENT CONTRIBUTION

The original apparatus of Amdur and Pearlman had several limitations which restricted the scope of the experiments which could be performed. First, the detector was stationary in the beam axis so that it was not possible to measure the angular distribution of scattering, but only total collision cross-sections. Under such conditions, only one point on the potential energy curve can be obtained from a cross-section value at a given

² L. Dunoyer, *Compt. rend.* 152, 594 (1911); *Le Radium* 8, 142 (1911).

³ See numerous references in R. G. J. Fraser, *Molecular Beams* (Methuen and Company, Ltd., London, 1937) and *Molecular Rays* (The Macmillan Company, New York, 1931).

⁴ H. S. W. Massey and C. B. O. Mohr, *Proc. Roy. Soc. A144*, 188 (1934). H. S. W. Massey and R. A. Buckingham, *Nature* 138, 77 (1936).

⁵ M. L. E. Oliphant, *Proc. Roy. Soc. A124*, 228 (1929).

⁶ O. Beeck, *Ann. der Phys.* (5) 19, 121 (1934).

⁷ H. Kallman and B. Rosen, *Zeit. für Phys.* 61, 61 (1930). H. Kallman, W. Lasareff, and B. Rosen, *Zeit. für Phys.* 76, 213 (1932).

⁸ A. Rostagni, *Zeit. für Phys.* 88, 55 (1934).

⁹ I. Amdur and H. Pearlman, *J. Chem. Phys.* 8, 7 (1940).

¹⁰ E. S. Lamar and O. Luhr, *Phys. Rev.* 46, 87 (1934).

¹¹ I. Amdur, *J. Chem. Phys.* 11, 157 (1943).

¹² I. Amdur and H. Pearlman, *J. Chem. Phys.* 9, 503 (1941).

beam velocity, in contrast to a series of points derivable from angular intensity measurements of a scattered beam at the same velocity. Second, the long scattering path, about 8.5 cm., introduced uncertainties in the estimation of the angular aperture subtended by the detector which were reflected in the final potential energy relations. Finally, it was necessary to make relatively large corrections to the observed scattered beam intensities because of the large pressure dependence of the detector which was not isolated from the scattering gas. It was therefore considered desirable to design a second scattering unit which would (1) permit accurately measurable travel of the detector with respect to the beam axis and (2) localize the scattering gas in a narrow chamber to simplify the estimation of the detector aperture and to permit the detector to be in a highly evacuated region at all times. In addition to eliminating restrictive features of the first apparatus, the second unit was designed to incorporate significant improvements among which were elimination of sources of mercury vapor by using a rapid oil diffusion pump and substituting a thermocouple gage and an ionization gage for the previous McLeod gages, and the use of a self-contained Pirani gage to measure the pressure of gas in the scattering chamber. It is the primary purpose of the present paper to describe this new apparatus and to indicate its potentialities by showing its performance characteristics. The authors feel that the preliminary results obtained show that their first objective has been obtained, namely, the development of an apparatus of the same quality as those used in thermal velocity beam research.

The beam of high velocity neutral particles is made in a manner analogous to that used by Lamar and Luhr¹⁰ for producing high velocity protons. A low voltage arc (20–60 volts, 0.5–1.5 amperes) is struck between a filament, at ground potential, and an anode in gas at 0.10–0.50 mm. pressure. Positive ions (0.10–0.30 ampere), produced primarily by electron collisions in the gas, are drawn to the cathode which is at a negative potential of 50–200 volts. Some of the positive ions (1.0–10.0 milliamperes) are drawn through a hemispherical nickel grid of 40 mesh screen mounted over an aperture in the cathode, and focused on the atom gun, an electrode with a small central canal. The negative potential on the atom gun may be varied from 200 to 2000 volts and some of the focused positive ions are

neutralized in the canal of the gun, either at grazing incidence with its walls, or without actual physical contact.¹³ The neutralization occurs without appreciable loss of kinetic energy, so that the beam emerging from the canal is a mixture of high velocity neutral atoms and positive ions which escaped neutralization. These ions are repelled by the top surface of the scattering chamber which acts as an ion mirror since it is at ground potential. Thus, the only high velocity particles entering the scattering chamber are neutral, accelerated gas molecules.

1. Structural Details of the Apparatus

The essential details of the present apparatus, with the exception of the electrical circuits, are shown in Figure 1. The arc section consists of two concentric brass tubes soldered to brass flanges at top and bottom. Hard solder is used except for the bottom joint of the outer tube, which is soft soldered. The section is provided with inlet and outlet tubes for circulating cooling water through the annular space, a $\frac{1}{2}$ inch cathode lead tube, and a 1 inch tube which leads to the scattering section through the large valve, 13. The portion of the 1 inch tube adjacent to the arc section contains an inlet tube for introducing gas and a connection, 12, for a thermocouple gage which measures the pressure in this section.

The arc section is fastened to the scattering section by 16 bolts which thread into the top flange of the scattering section. The junction of the two sections is made vacuum tight by a lead gasket, 0.040" thick. The filament adjuster, 1, is fastened to the arc section by a split steel plate and a similar arrangement of bolts and gasket.

It has been previously found⁹ that the beam intensity frequently varied with the distance between the filament, 4, and the hemispherical grid, 5. A filament adjuster was therefore included in the present apparatus to permit accurate adjustment and measurement of the filament position. The adjuster is housed in a 5 inch length of brass tubing soft soldered into a brass flange. Vertical motion in vacuum is obtained by turning the knurled graduated knob at the top of the adjuster, since the drive shaft is pinned to a vacuum tight plate at the lower, free end of a bellows whose upper, fixed end is soldered peripherally to the inside of the housing. Eyelets, consisting of metal to glass seals, are used to bring leads from the filaments and anode, 2, through

¹³ M. L. E. Oliphant and P. B. Moon, *Proc. Roy. Soc. A127*, 388 (1930).

the bottom plate. A radiation baffle is fastened below the plate to prevent the eyelets from being short circuited by evaporated and sputtered metal from the arc. The filament leads, protected from shorting to the anode by quartz sleeves, pass freely through holes in the anode as the bellows is compressed or extended. The required free-

dom of motion in this region with respect to the fixed anode is supplied by a phosphor bronze spring which serves as the anode lead. The adjuster permits about 1 inch of filament travel from a zero position about $\frac{1}{2}$ inch above the grid. A metal index, fastened to the top of the drive shaft, indicates relative filament heights to

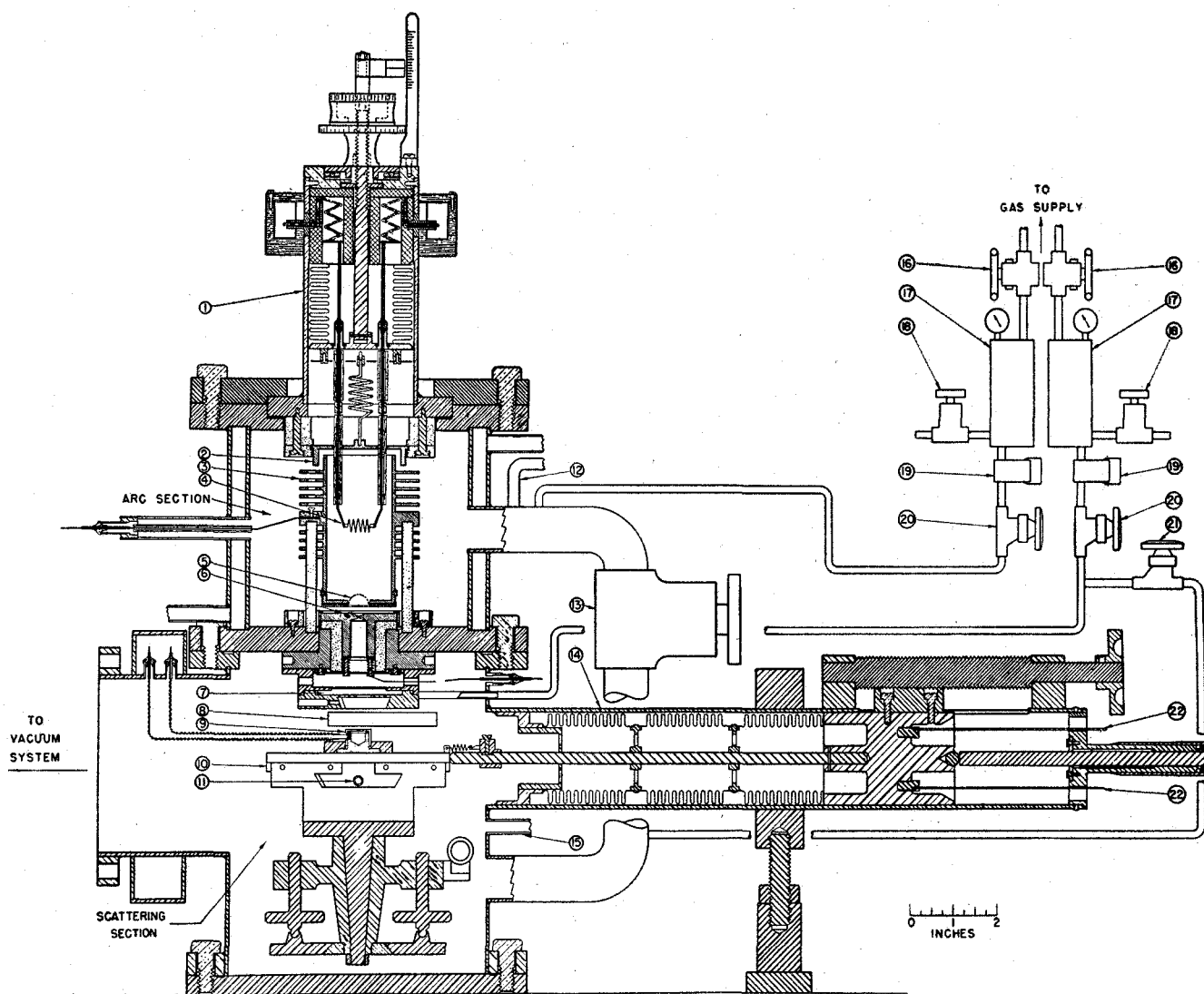


FIGURE 1. Details of high velocity molecular beam apparatus.

- | | | |
|-----------------------|----------------------------------|--------------------------------------|
| 1. Filament adjuster | 9. Detector | 17. Ballast tanks |
| 2. Anode | 10. Longitudinal slide | 18. Gas supply pump-out valves |
| 3. Cathode | 11. Transverse slide | 19. Throttle valves |
| 4. Filament | 12. Thermocouple gage connection | 20. Low pressure shut-off valves |
| 5. Grid | 13. Arc section by-pass valve | 21. Scattering chamber by-pass valve |
| 6. Atom gun | 14. Longitudinal slide drive | 22. Counterweight cables |
| 7. Scattering chamber | 15. Ionization gage connection | |
| 8. Condensers | 16. Gas supply shut-off valves | |

twentieths of an inch on a graduated vertical standard; measurements to thousandths of an inch are read from the graduated drum of the knurled knob.

The apparatus has been designed to permit measurements of positive ion scattering by placing the atom gun at ground potential, the filament at variable positive potential, and the anode and cathode at appropriate potentials with respect to the filament, thereby eliminating the ion mirror action of the grounded scattering chamber. It is therefore necessary to provide for both flexibility and high voltage insulation of the filament and anode leads in the section of the filament adjuster above the vacuum tight bellows plate. This is accomplished by fastening coiled, stranded lead wires to the ends of the rigid leads from the filament and anode and encasing each of the three coils in wells drilled in a Lucite plastic cylinder which fits inside the adjuster housing and rests on the top bellows convolution. A Lucite disk covers the cylinder making it impossible for any portion of a coil to leave its well since the point at which the lower end of each coil is fastened to its rigid lead never leaves the well. At the top of the Lucite cylinder each stranded lead wire is held by the disk in a groove which leads into holes in the cylinder walls. The wire is fed through these holes and out through openings in the brass housing. Bakelite bushings prevent the leads from shorting to the brass walls. A Bakelite annular ring, suitably partitioned to segregate the three leads, is anchored to the housing and receives a conduit carrying leads from the filament and anode power sources. Soldered connections are made inside the partitions of the annular ring simply by removing the top cover.

The most suitable filaments were found to be standard oxide coated filaments used in type 866A mercury rectifier tubes. The filaments were kindly supplied without charge by the Radio Corporation of America.

The cathode, 3, was machined from aluminum and provided with cooling fins, one of which is $\frac{5}{16}$ " thick as compared with $\frac{1}{16}$ " for the remainder. The cathode is supported about $\frac{1}{10}$ " above the atom gun by three $\frac{1}{4}$ " diameter Isolantite ceramic rods. These pass through holes, spaced 120° apart, drilled through the bottom four fins and seat, at their upper ends, in the thick fin, while their lower ends rest in the floor of the arc section. The thick cathode fin also contains a set screw for fastening the cathode lead. The hemi-

spherical screen grid, 5, which focuses positive ions on the atom gun, 6, is fastened over a $\frac{1}{2}$ " opening in the bottom of the cathode by a close fitting aluminum cap with a $\frac{1}{2}$ " center hole.

The anode is a cap machined from aluminum of size sufficient to permit at least $\frac{1}{10}$ " clearance between any point on it and any point on the cathode. It is provided with a ledge and peripheral boss to locate it between two rings of lava which are fastened to the flange of the filament adjuster. The arrangement insures proper alignment of the anode relative to the cathode. A second boss toward the center of the anode is tapped to receive the phosphor bronze spring lead.

The aluminum atom gun, shown in greater detail in Figure 2A, is $1\frac{3}{4}$ " in diameter across the face and $1\frac{3}{8}$ " long. The central canal is 0.020" in diameter and 0.120" long and is well rounded on the top to reduce discharge to the cathode. An insulating bushing, machined from a low vapor pressure plastic, Teflon, separates the atom gun from the aluminum insert which threads into the lower flange of the arc section and supports the scattering chamber, 7. The high voltage lead enters through a metal-glass seal in the scattering section and is connected to a brass washer held by spring contact against the bottom of the atom gun. A glass ring, fastened to the bottom of the aluminum insert, holds and insulates the high voltage washer contact. Pressure against the washer is obtained by forcing the atom gun down against the tension of the springs with a lava ring which bears on the face of the gun. The under surface of the gun face and the upper and under surfaces of the bushing into which the gun fits are made as smooth as possible to minimize leakage of gas from the arc section to the scattering section.

The scattering chamber consists of two parts which are soldered together. The upper section is cylindrical in shape and contains a 0.020" entrance hole for the beam. Twenty $\frac{1}{4}$ " holes, equally spaced, have been drilled around the periphery of this section to permit rapid pumping of the region between the atom gun and the entrance to the scattering chamber. Two of the holes have been converted into a slot to permit passage of a glass vane, $\frac{1}{4}$ " wide, $1\frac{1}{2}$ " long and $1/32$ " thick, which serves as a shutter to cut out the beam. The vane is moved in and out of the beam by a helical drive bellows arrangement not shown in the figure. The bottom section of the scattering chamber is $2\frac{3}{4}$ " square with an annular ring $2\frac{1}{2}$ " O. D. and $\frac{1}{4}$ " wide which telescopes

into the upper section. The bottom section contains the exit slot for the beam and two adjustable jaws which cover the slot to form a long, narrow slit. The important dimensions of the scattering

chamber are shown in Figure 2A and in Figure 2B in which the bottom section of the scattering chamber has been turned through 90° to show the manner in which the jaws close over the exit

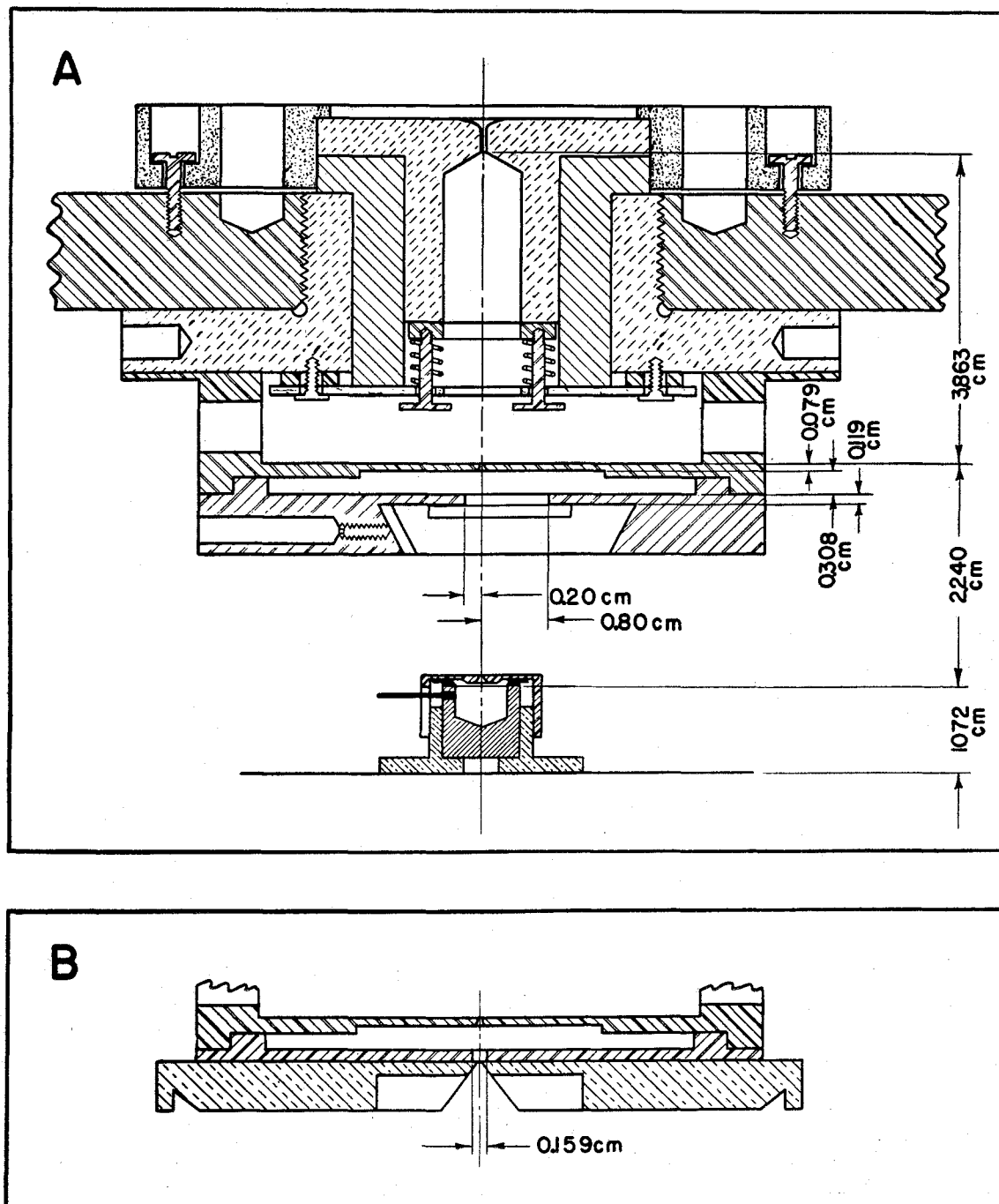


FIGURE 2. Details of atom gun, scattering chamber, and detector. A. Critical dimensions and distance relations. B. Scattering chamber exit slit jaws.

slot to form the exit slit. The pressure of the scattering gas in the region between the upper and lower sections of the scattering chamber is measured with a self-contained, compensated Pirani gage which also forms part of a circuit for measuring the temperature of the scattering gas. The details of this gage will be described under performance characteristics of the apparatus.

Two condenser plates, 8, sweep out of the beam any electrons or positive ions resulting from ionization action of high speed neutrals, as well as electrons emitted by metallic surfaces upon being struck by high energy particles. The plates are made of chromium plated brass and are $2\frac{1}{2}$ " long, $\frac{3}{8}$ " wide, and $\frac{1}{32}$ " thick. They are so placed that the separation distance between the inside faces, 0.080", is symmetrical about the beam, while the length is asymmetrically distributed about the beam, about $\frac{3}{4}$ " on the side toward the vacuum system. Potential differences up to 2000 volts may be impressed across the condensers.

The neutral beam intensity is measured by the detector, 9, (to be described later) which is mounted on a movable slide, 10. Longitudinal motion of the detector, in the direction parallel to the length of the exit slit, is obtained with a worm drive bellows arrangement, 14, which permits 2" of travel, 0.3" on the vacuum system side, and 1.7" on the worm drive side of the beam axis. A micrometer measures the position of a hardened steel ball spun into the center of the movable piston actuated by the worm drive, thereby determining relative longitudinal positions of the detector to 0.0005". A 50 pound counterweight is suspended from stranded brass cables, 22, over a pulley system, to balance the inward thrust of the atmosphere and permit easy motion of the worm drive. Transverse motion of the detector, in the direction perpendicular to the length of the exit slit, is obtained with a small micrometer bellows drive whose shaft is attached to the other movable slide, 11, of the detector carriage. This arrangement permits transverse motion of the detector of about 0.040" on either side of the beam axis and enables relative positions to be determined to 0.0005".

A 12 bolt, lead gasketed, flange combination connects the scattering section to the vacuum system consisting of a 4 inch oil fractionating diffusion pump, equipped with a water cooled baffle and backed with a Hypervac-20 forepump. The diffusion pump is protected against failure of its cooling system or excessive rise in forepressure.¹⁴ The pumping speed of the vacuum

system is estimated at 100 liters of air per second (the decrease from 275 liters per second, the nominal rating of the diffusion pump, is due to the presence of the baffle) and is sufficient to maintain a pressure of 6×10^{-5} mm. of helium in the scattering section with a helium pressure of 0.1 mm. in the arc section. A tube, 15, leads directly from the scattering section to an ionization gage which reads the low pressures in this section of the apparatus.

There are several features of the scattering section not shown in Figure 1 or previously described. These include six metal-glass seals for taking out the electrical leads from the scattering chamber Pirani gage network and the condensers and a Pyrex observation window $2\frac{1}{2}$ " in diameter and $\frac{3}{8}$ " thick which is clamped and gasketed in a 12 bolt flange on a large tubulation in the wall of the scattering section.

Separate gas supply systems are provided for the arc section and scattering chamber to permit scattering experiments for systems of unlike molecules. When possible, the gases are stored in small, high pressure steel cylinders, connected, through reducing valves, to the shut off valves, 16, which segregate the gas in the 500 cc. ballast tanks, 17, from the main supply, and are useful in preventing the pressure in the ballast tanks from building up in the event of a leak across the reducing valves of the storage cylinders. The flow of gas is regulated by the needle valves, 19, which have 500 : 1 tapers and provide accurate control of the pressure in the arc section and scattering chamber. The throttled gas streams enter the apparatus through a second pair of shut-off valves, 20. Pump-out valves, 18, are provided for evacuating the ballast tanks before filling them to a pressure slightly above atmospheric. A by-pass valve, 21, permits the scattering chamber to be quickly evacuated to obtain unscattered beam intensities for comparison with scattered beam intensities. All valves are packless, either diaphragm or bellows type, are made from brass forgings or machined from brass stock, and are individually tested for vacuum tightness.

Except for the diffusion pump protection device and a motor-generator set which supplies 100 volts and 200 volts D. C. for the anode and cathode, all electrical controls and power supplies are housed in a standard, mobile relay rack. Switches for the arc section are high voltage relays, operated from 6 volt transformers, which reduce

¹⁴ I. Amdur, Rev. Sci. Inst. 18, 66 (1947).

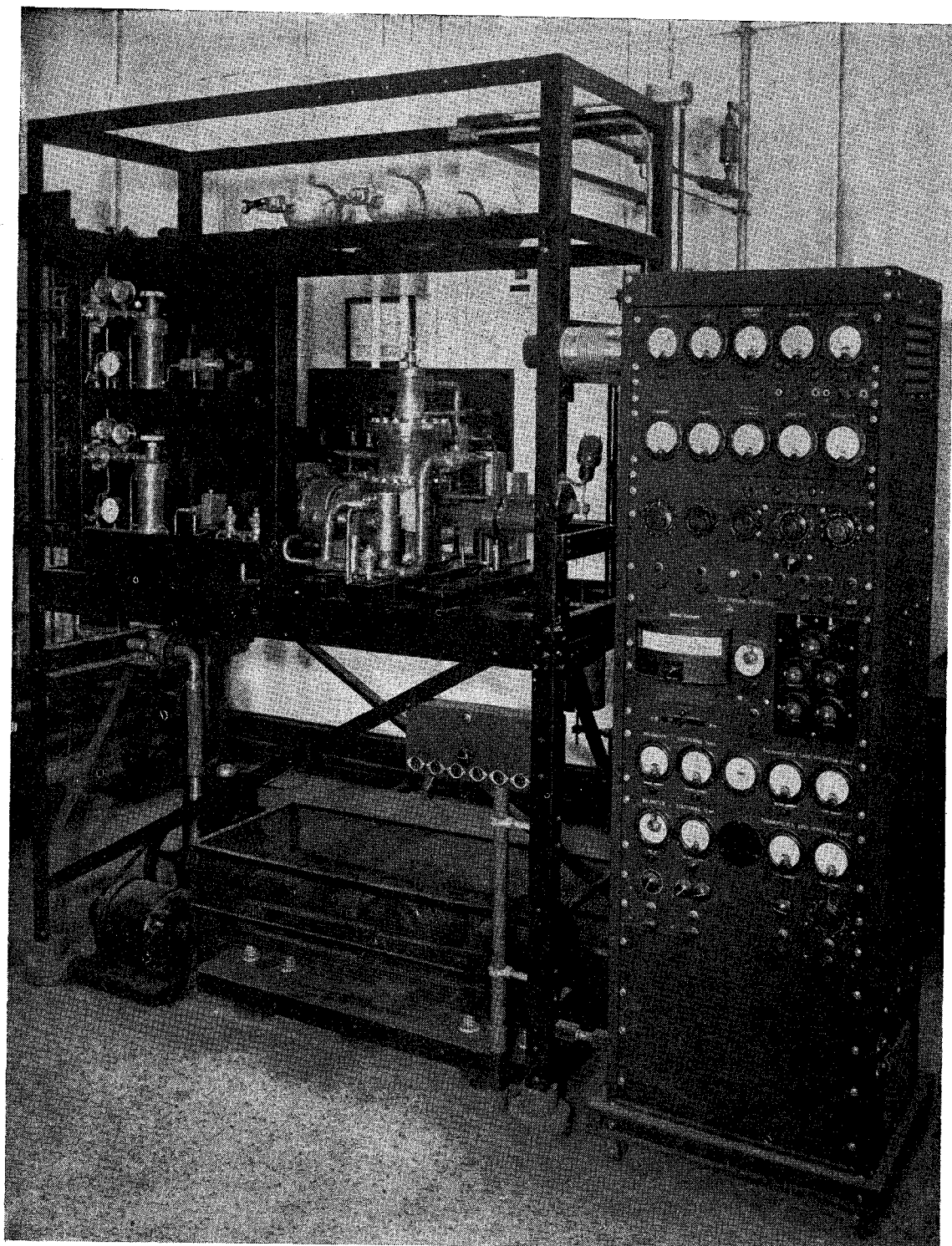


FIGURE 3. Apparatus and controls.

danger of shock as well as arcing difficulties encountered when slow moving, conventional switches are used in high voltage, high current circuits. The use of separate 100 and 200 volt D. C. generators (instead of the laboratory D. C. mains) permits the anode and cathode to remain at their same potentials relative to the filament when the atom gun is grounded and the filament raised to variable positive potential in the measurement of positive ion scattering. The beam apparatus has been mounted on a steel angle iron frame which rests on large bakelite supports and is electrically isolated, since water leads to and from the arc section and diffusion pump are interrupted with 12 inch sections of glass tubing. It is therefore possible to place the entire apparatus at positive or negative potential for special purposes such as a study of the effectiveness of the top surface of the scattering chamber as an ion mirror. Figure 3 is a photograph of the beam apparatus and its electrical controls. The diffusion pump is concealed by the panel of ballast tanks and valves for the gas supply systems, and a special galvanometer amplification arrangement¹⁵ for measuring the detector response does not appear since it is in a section of the laboratory removed, as far as possible, from the electrical fields of the generators and power supplies.

2. Performance Characteristics of the Apparatus

a. Detector Characteristics

Two types of beam detectors have been built which operate by converting the kinetic energy of the high velocity beam particles into heat. One type is a single junction radiation vacuum thermocouple¹⁶ and the other, a compensated vacuum bolometer.¹⁷ Three vacuum thermocouples of different construction have been investigated. One, A, contains a circular receiver 0.279 cm. in diameter supported by one Chromel P and two constantan wires and masked with a circular opening 0.163 cm. in diameter; the second, B, contains a circular receiver 0.102 cm. in diameter supported by one Chromel P and one constantan wire and masked with a circular opening 0.051 cm. in diameter; and the third, C, which contains no receiver, was made

by using a condenser discharge to butt weld a 0.0015 cm. diameter Chromel P wire, 0.318 cm. long, to a 0.0013 cm. diameter constantan wire, 0.318 cm. long, and is masked symmetrically about the weld with a rectangular opening, 0.051 cm. wide and 0.635 cm. long, whose long axis is perpendicular to the thermocouple. The welded detector has been used for most of the preliminary measurements with the present apparatus and is shown in Figure 2A in the axis of the beam path. The wires in thermocouples B and C are soldered to copper hemi-cylinders, separated by a mica spacer 0.001" thick and pressed into a brass container which is insulated from the copper inserts by additional 0.001" mica spacers. The bolometer, D, has a detecting element consisting of a blackened platinum wire 5.6×10^{-4} cm. in diameter and 0.476 cm. long which, like the welded thermocouple, acts as its own receiver. The detectors were tested by irradiation in vacuum with light from a standard lamp in accordance with previously described procedures.^{16,17} The chief purpose in building the four detectors was to provide a method of varying the angular aperture of the detecting system since it has been shown¹⁸ that experimentally determined cross-sections are functions of this aperture.

The results of room temperature tests on the four detectors are summarized in Table I. The angular apertures are the half angles subtended by the detector with respect to a point on the beam axis in the center of the gas confining region of the scattering chamber, namely, 0.253 cm. below the top surface of the upper section. These apertures differ by less than one per cent from values computed by averaging linearly over the 0.506 cm. distance which the beam travels in passing through the upper and lower sections of the scattering chamber. The radiant energy absorbed per second by each detector is given by $7.22 \times 10^{-5} \times 0.67 \times$ exposed area since the tabulated responses have been reduced to a common energy density falling per second on each detector, namely, 7.22×10^{-5} watts/cm.² The detectors also have a common absorptivity, 0.67, which is characteristic of their aquadag coatings.

¹⁵ I. Amdur and H. Pearlman, *Rev. Sci. Inst.* **9**, 194 (1938).

¹⁶ I. Amdur and H. Pearlman, *Rev. Sci. Inst.* **10**, 174 (1939).

¹⁷ I. Amdur and C. F. Glick, *Rev. Sci. Inst.* **16**, 117 (1945).

¹⁸ H. S. W. Massey and C. B. O. Mohr, *Proc. Roy. Soc. A* **141**, 434 (1933). H. S. W. Massey and C. B. O. Mohr, reference 4. R. G. J. Fraser and L. F. Broadway, *Proc. Roy. Soc. A* **141**, 626 (1933). L. F. Broadway, *Proc. Roy. Soc. A* **141**, 634 (1933). W. H. Mais, *Phys. Rev.* **45**, 773 (1934). S. Rosin and I. I. Rabi, *Phys. Rev.* **48**, 373 (1935).

TABLE I
CHARACTERISTICS OF BEAM DETECTORS

Detector	Angular Aperture	Exposed Area (cm. ²)	Power Absorbed (watts)	Response (volts)	Sensitivity (volts/watt)
A	2.35 degrees	2.09×10^{-2}	1.01×10^{-6}	1.73×10^{-6}	1.71
B	44.0 minutes	2.04×10^{-3}	9.85×10^{-8}	6.37×10^{-7}	6.47
C	1.21 minutes	7.14×10^{-5}	3.45×10^{-9}	1.56×10^{-7}	45.2
D	28.9 seconds	2.67×10^{-4}	1.29×10^{-8}	1.28×10^{-6}	99.2

For each detector, the room temperature sensitivity is constant with respect to radiation density flux in the range 0 to 7.22×10^{-5} watts/cm.² by actual test.

In the case of a bolometer, the response is a function of the heating current. The value given for detector D in Table I is the maximum response and was obtained with a heating current of 0.92 milliamperes which produced a temperature rise of 55°.

b. Arc Characteristics

Since, to date, helium has always been used both in the arc section and in the scattering section, the performance characteristics of the apparatus refer to that gas. For other gases, the characteristics would differ in specific detail but not in general character.

After inserting a new filament, the large by-pass valve, 13, is opened and both sections of the apparatus are evacuated to a pressure below 10^{-5} mm. The filament is then "broken in" by careful heating to decompose its carbonate mixture coating into an active oxide coating. After the activation of a new filament, which requires about 15 minutes, the by-pass valve is closed and gas is admitted to the arc section at a pressure of about 0.4 mm. The anode and cathode are then shorted together and connected to the 100 volt D. C. source so that an arc is struck between the filament and the shorted electrodes. The shorting procedure has been found helpful in starting the arc, presumably because it provides a very much greater anode surface and eliminates the negative field which tends to return electrons to the filament. The arc is run in this manner until conditions become stable, after which the cathode is unshorted from the anode and operated at its proper negative potential. It is extremely important to prevent the anode voltage from rising much above 40 volts, otherwise bombardment of the filament by large currents of high energy positive ions will strip the oxide coating and deactivate the filament. The tendency toward high anode voltages is very pronounced when a new filament is first used, due, possibly, to gaseous impurities

liberated from the metal surfaces upon bombardment by ions. The situation is remedied by evacuating the arc section through the large valve to eliminate the impure gas mixture. After several cycles in which the arc is restarted following the removal of impure gas, the anode voltage assumes a value of 40 volts or less and the arc continues to start and operate satisfactorily as long as air, or other harmful foreign gas such as water vapor, is not admitted to the arc chamber. This is accomplished by keeping the entire apparatus under high vacuum when the arc is not operating. It is because of the necessity for keeping the vacuum pumps in constant operation, that the protection device for the diffusion pump has been included in the apparatus. About 10 hours of arc operation are required to stabilize the arc and metal surfaces after insertion of a new filament, after which about an hour is required each time the arc is restarted after a shut down period exceeding several hours. After the 10 hour conditioning period, it is possible to decrease the gas pressure in the arc section to about 0.2 mm. to obtain larger detector responses without loss of arc stability. There is some evidence that the insertion of a copper liner inside the cathode results in lower anode voltages due, possibly, to the relative ease, compared to aluminum, with which copper sputters. The sputtering of the copper tends to produce a clean cathode surface, but since some of the sputtered metal deposits on the cooler turns of the filament and covers active oxide, much of the advantage with respect to increased filament life is probably lost. With proper precautions such as those described, filament life in excess of 100 hours can be obtained.

The following record of the first 19 running hours of an arc using a copper lined cathode and a filament which lasted for 98 running hours, illustrates average satisfactory arc behavior during the early life of a filament.

Typical atom gun-detector characteristics (obtained with the detector in the beam axis and the scattering chamber evacuated) for a properly functioning apparatus are shown in Figure 4 and correspond to the following arc conditions:

TABLE II

ARC CHARACTERISTICS FOLLOWING INSERTION OF A NEW FILAMENT

Time Hr. Min.	Pressure Mm.	Filament		Anode		Cathode		Remarks
		Amp.	Volts	Amp.	Volts	Amp.	Volts	
0	5×10^{-4}	3.0	0.7	—	—	—	—	Activation of filament. Large by-pass valve open.
2	1×10^{-4}	4.0	1.4	—	—	—	—	
4	1×10^{-4}	5.0	2.2	—	—	—	—	
7	5×10^{-4}	6.0	3.1	—	—	—	—	
9	1×10^{-4}	7.0	3.75	—	—	—	—	
14	1×10^{-4}	8.0	4.4	—	—	—	—	
15	1×10^{-4}	7.0	3.75	—	—	—	—	
18	0.42	7.0	3.7	1.0	21	Sh. to anode		Large by-pass valve shut. Gas in arc section.
20	0.43	7.0	3.7	1.0	25	Sh. to anode		Arc turned off. Arc section pumped out.
25	0.27	7.0	3.7	1.0	21	Sh. to anode		Arc restarted.
39	0.43	7.1	3.7	0.85	52	0.08	140	Cathode unshorted.
42	0.30	7.0	3.7	1.0	42	0.08	142	Arc turned off. Arc section pumped out
1 2	4×10^{-3}	7.0	3.7	—	—	—	—	
2 4	2×10^{-3}	7.0	3.7	—	—	—	—	Difficulty in outgassing.
2 35	0.31	8.0	4.3	0.45	40	0.08	140	Arc restarted.
3 50	0.40	8.0	4.3	0.50	33	0.08	144	
6 35	0.45	7.7	4.1	0.80	44	0.11	140	Arc turned off.
0	0.42	7.5	3.9	1.0	24	Sh. to anode		Arc started next day.
20	0.35	7.5	3.9	0.85	36	0.13	120	Cathode unshorted.
4 5	0.31	7.5	4.0	0.90	29	0.14	120	
5 45	0.41	7.0	3.7	0.87	30	0.22	120	
8 5	0.31	7.0	3.7	0.79	37	0.22	124	Arc turned off. Atom gun draws 2 ma. at 800 volts.
0	0.42	7.5	4.2	0.90	38	0.22	120	Arc started next day.
2 3	0.41	7.5	4.2	1.0	29	0.25	118	Atom gun draws 2.1 ma. at 800 volts.
4 33	0.36	7.0	3.8	0.89	38	0.28	120	Atom gun draws 2.4 ma. at 800 volts.

pressure—0.25 mm.; filament—7.5 amp., 4.65 volts; anode—1.38 amp., 32 volts; cathode—0.30 amp., 170 volts. For a given arc pressure, curves of the same shape are obtained for different steady arc conditions.

The curves in Figure 4 can be fitted with the following relations:

$$I = 0.40 + 2.00 \times 10^{-3} V \text{ milliamperes} \quad (\text{A}) \quad (3)$$

$$E/I = 1.48 \times 10^{-2} e^{2.85 \times 10^{-3} V} \text{ microvolts/milliampere} \quad (\text{B}) \quad (4)$$

$$E = (5.92 \times 10^{-3} + 2.96 \times 10^{-5} V) e^{2.85 \times 10^{-3} V} \text{ microvolts} \quad (\text{C}) \quad (5)$$

where I , is the atom gun current, E , the electromotive force of the detector, and V , the atom gun voltage. For the particular geometry of the present apparatus, these results indicate that at low voltages the efficiency of neutralization (defined as the fraction of energy striking the atom gun which appears in the form of high speed neutrals) decreases with increasing voltage while at higher voltages the efficiency increases, due, possibly, to improved focusing by the screen grid. This conclusion is obtained in the following way.

The fraction, F , of atom gun energy which is converted into neutral beam energy is $aE/(IV)$

where a is a voltage independent constant characteristic of apparatus geometry. This fraction is given by

$$F = aE/(IV) = be^{2.85 \times 10^{-3} V}/V \quad (6)$$

where $b = 1.48 \times 10^{-2}a$, and the rate of change of the fraction by

$$dF/dV = F(2.85 \times 10^{-3} - 1/V). \quad (7)$$

This rate of change is negative below 350 volts and positive above, suggesting the previously mentioned change in efficiency of neutralization with increasing voltage.

For a different set of arc conditions, namely: pressure—0.24 mm.; filament—7.5 amp., 4.5 volts; anode—0.81 amp., 40.5 volts; cathode—0.24 amp., 172 volts, the same general results were obtained, as shown by the following relations:

$$I = 0.32 + 1.93 \times 10^{-3} V \text{ milliamperes} \quad (8)$$

$$E/I = 1.57 \times 10^{-2} e^{2.83 \times 10^{-3} V} \text{ microvolts/milliampere} \quad (9)$$

$$E = (5.03 \times 10^{-3} + 3.03 \times 10^{-5} V) e^{2.83 \times 10^{-3} V} \text{ microvolts.} \quad (10)$$

It is possible to obtain stable arc conditions and reproducible atom gun-detector characteristics for arc section pressures ranging from about 0.08

to 0.50 mm. The neutral beam intensity, however, is a fairly strong function of this pressure. For example, for an unscattered beam at 800

volts, an arc section pressure of 0.21 mm. produces a maximum detector response which decreases by 40 per cent at 0.42 mm. and by 20

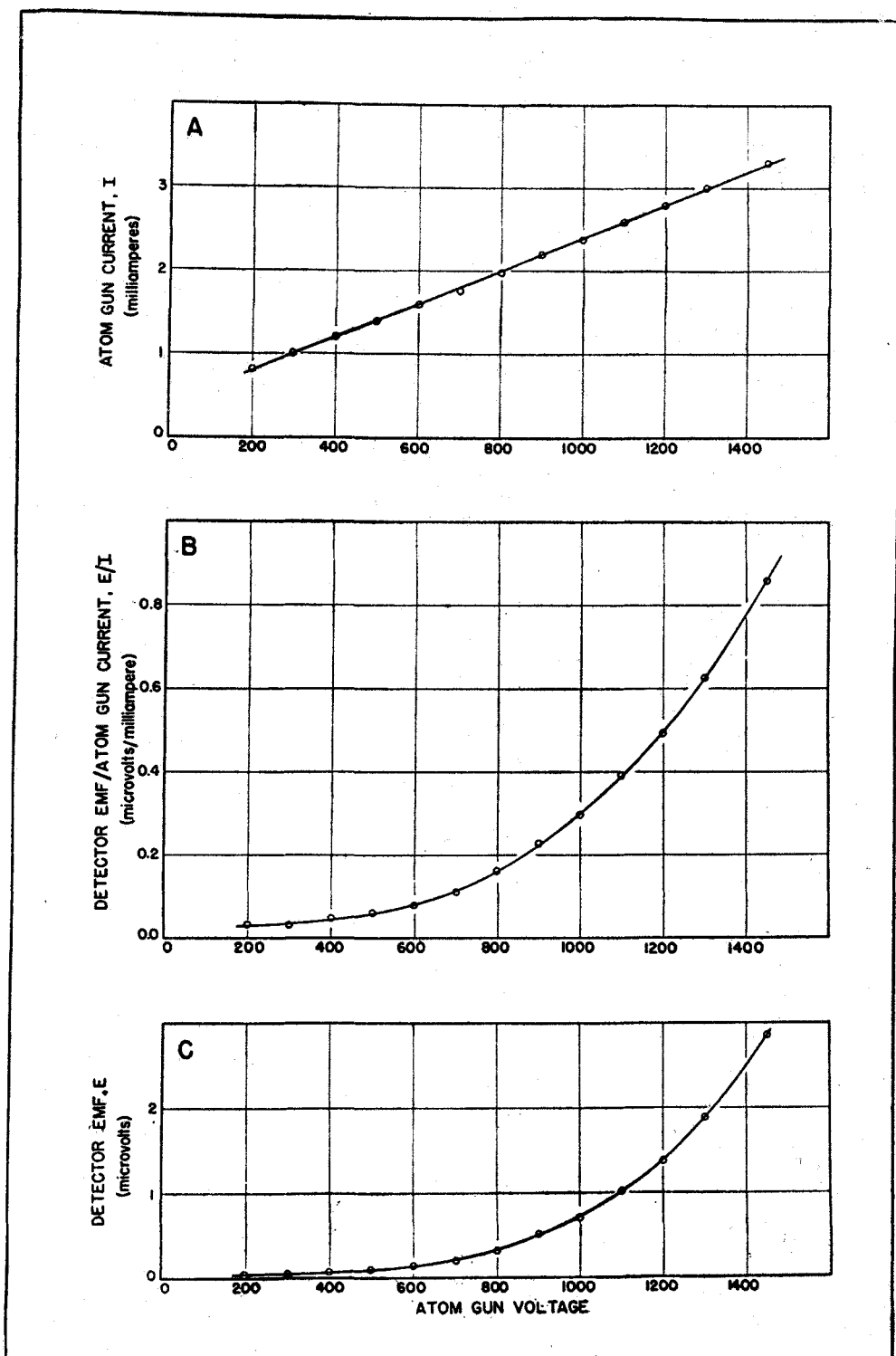


FIGURE 4. Typical atom gun-detector characteristics.

per cent at 0.09 mm. The decrease at higher pressures is probably due to scattering of high velocity ions on their way to the atom gun, and the decrease at low pressures, to the smaller number of positive ions which pass through the screen in preference to being neutralized at the cathode walls, as suggested by enhanced cathode currents at low pressures. Whenever possible, therefore, an arc section pressure of about 0.2 mm. is used to obtain maximum detector responses for any given set of arc conditions.

c. Pirani Gage Characteristics

The self-contained Pirani gage which measures the pressure of gas in the scattering chamber has been described in detail elsewhere.¹⁹ It consists of a platinum wire, 1.37×10^{-3} cm. in diameter and 4.57 cm. long, suspended between the upper and lower sections of the chamber. A platinum wire compensator, in thermal contact with the walls of the scattering chamber, and two fixed manganin resistors are combined with the gage wire to form a Wheatstone bridge network which is in balance when the gage wire is about 2 degrees hotter than the compensator. For a given compensator temperature and a given gas, the scattering pressure is a single valued function of the bridge current at balance. Over a limited pressure range, it is possible to use an empirical relation which, for the present type of gage network, has the simple form

$$P = aI_B^2 - b \quad (11)$$

where P is the pressure and I_B , the bridge current at balance. The constants a and b are characteristic of each gas and depend only upon the temperature. This temperature dependence may be deduced in the following manner.

When current, I , flows through the Pirani gage wire of resistance R , the energy balance may be written in the form

$$IR = A + B + C + D \quad (12)$$

where

A = radiation loss

B = wire conduction loss at zero pressure

C = additional wire conduction loss at pressure P

D = gas conduction loss at pressure P .

The heat flow problem formulated in Equation (12) has been previously analyzed in discussing the characteristics of a compensated bolometer,¹⁷

and the results obtained indicate that, for the present gage, C may be treated as a constant small fraction (about 0.1) of D for pressures up to about 0.1 mm., the probable upper limit of scattering pressure which will be used in the apparatus. Equation (12) may therefore be written

$$IR = I_0^2 R + K\alpha P \bar{\Delta}t / \bar{T}^{\frac{1}{2}} \quad (13)$$

where I_0 is the current through the gage wire at zero pressure at bridge balance, α , the accommodation coefficient of the gas on the gage wire, $\bar{\Delta}t$, the average temperature excess of the gage wire with respect to the compensator at temperature t , $\bar{T}$, the average gas temperature (which may be set equal to $273 + t + \bar{\Delta}t/2$ or $274 + t$), and K , a constant for each gas which is independent of both temperature and pressure.

The current which is read in the apparatus is not the gage wire current, I , but the total bridge current, I_B , whose relation to I is expressed by

$$I = \frac{I_B}{2.525 [1 + 2.12 \times 10^{-3}(t - 26)]} \quad (14)$$

The gage resistance, R , and the average temperature excess, $\bar{\Delta}t$, are temperature functions given by

$$R = 36.483 [1 + 3.60 \times 10^{-3}(t - 26)] \text{ ohms} \quad (15)$$

and

$$\bar{\Delta}t = 2.114 [1 + 3.63 \times 10^{-3}(t - 26)] \text{ degrees.} \quad (16)$$

Since 26° C. was the reference temperature at which the bridge characteristics were determined, the corresponding reference value for $\bar{T}$ must be taken as 300° K., whereupon Equation (13) reduces to

$$I_B^2 = I_{B(0)}^2 + K'\alpha P [1 + 2.60 \times 10^{-3}(t - 26)] \quad (17)$$

where $K' = K/46.88$ and where $I_{B(0)}$ by actual measurement is found to conform to the relation

$$I_{B(0)} = 1.977 [1 + 3.69 \times 10^{-3}(t - 26)] \text{ milliamperes.} \quad (18)$$

Equations (17) and (18) lead to the following equation for converting a bridge current, I_B , measured at temperature t and pressure P , to a corrected current, I_B^* , referred to 26° C and the same pressure:

$$I_B^{*2} = \frac{I_B^2}{1 + 2.60 \times 10^{-3}(t - 26) - 18.7 \times 10^{-3}(t - 26)}. \quad (19)$$

Equation (17) does not transform directly into Equation (11) because the accommodation coefficient

¹⁹ I. Amdur, M. M. Jones and H. Pearlman, J. Chem. Phys. 12, 159 (1944).

cient, α , is pressure dependent in the range of present interest, 0 – 0.1 mm.²⁰ Yet, calibration results for ten gases, when corrected by Equation (19) to 26° C., gave very satisfactory straight line plots of P vs I_B^{*2} in the pressure range 0.008 – 0.12 mm., showing that the form of Equation (11) is valid. The ratios of b/a did not equal $I_{B(0)}^{*2}$, (1.977 ma.),² however, and the straight line relation must therefore be considered empirical. That it is obtained at all is probably due to the fact that no attempt was made to force the constants a and b or the ratio b/a to adhere to theoretical or predetermined values and that the moderate pressure dependence of α was therefore absorbed in the mutual departure of a and b from such values.

The calibration results for the ten gases are summarized in Table III in terms of the values of the constants a and b in Equation (11) which define the best straight lines through the experimental points corrected to 26° C. Fifty experimental values were available in the desired pressure range, of which two, one each for helium and xenon, were discarded as being excessively in error. The second column lists the number of experimental values which were used in determining the constants for each gas, while the last two columns record absolute deviations of calculated pressures from experimental values.

TABLE III
PIRANI GAGE CALIBRATION AT 26° C. FOR
0.12 MM. > P > 0.008 MM.

Gas	No. of points	a	b	Av. Dev.	Max. Dev.
		mm.-(ma.) ²	mm.	%	%
Helium	6	0.01093	0.04500	1.4	3.5
Neon	5	0.01362	0.05466	1.0	1.9
Argon	4	0.01567	0.06323	1.8	2.5
Krypton	5	0.02245	0.09160	0.9	1.4
Xenon	5	0.02776	0.1160	1.4	2.7
Hydrogen	5	0.006600	0.02700	1.6	2.5
Deuterium	5	0.007335	0.03054	0.8	1.3
Nitrogen	5	0.009813	0.04023	1.4	2.3
Carbon monoxide	4	0.009771	0.04070	0.2	0.4
Oxygen	4	0.01006	0.04027	0.8	1.2

At any temperature two readings of the bridge current are required to determine the scattering pressure. One reading, $I_{B(0)}$, at zero pressure serves to define t through Equation (18), so that the other reading, I_B , at pressure P , may be corrected to I_B^* at 26° C. through Equation (19). The values of a and b appropriate to the gas are then selected from Table III and combined with I_B^* to calculate P from Equation (11).

²⁰ I. Amdur, J. Chem. Phys. 14, 339 (1946).

d. Scattering Section Pressure Characteristics

Whenever possible, the intensity of a beam which has been attenuated by passing through a layer of scattering gas is referred to the intensity of the unscattered beam to eliminate the difficult and unnecessary task of measuring absolute intensities. When it is not feasible to obtain an intensity measurement at essentially zero scattering pressure, the ratio of intensities at two known pressures serves equally well. This is illustrated by the following expressions for estimating the scattering mean free path at unit pressure and 273° K., L_v , of a beam particle which has traversed a uniform scattering region of length x :

Case 1—Scattered intensity, I , at pressure P and temperature T ; reference intensity, I_0 , at zero pressure.

$$I/I_0 = \exp [-(273x/L_v)(P/T)]. \quad (20)$$

Case 2—Scattered intensity, I_1 , at pressure P_1 and temperature T_1 ; reference intensity, I_2 , at pressure P_2 and temperature T_2 .

$$I_1/I_2 = \exp [-(273x/L_v)(P_1/T_1 - P_2/T_2)]. \quad (21)$$

In the present apparatus the 0.020" hole in the atom gun permits sufficient gas to flow from the arc section into the scattering section to cause significant scattering of the beam even when gas is not admitted into the scattering chamber, and the equivalent of Equation (21) must be used for mean free path calculations. The relation of the scattering section pressure to the arc section pressure under these conditions was determined for helium from readings of the thermocouple and ionization gages and found to conform to the type of relation required for free molecule flow. The actual relation may be written

$$P_{SS}^{\circ} = 6.11 \times 10^{-4} P_{AS} \quad (0.10 \text{ mm.} < P_{AS} < 0.43 \text{ mm.}) \quad (22)$$

where P_{SS}° is the scattering section pressure of helium due to pressure P_{AS} in the arc section when gas is not admitted to the scattering chamber. Similarly, by eliminating the flow of helium into the arc section and admitting gas to the scattering chamber, the increase in scattering section pressure, ΔP_{SS} , due to gas in the scattering chamber at pressure P_{SC} was determined from readings of the Pirani and ionization gages. The actual relation was found to be

$$\Delta P_{SS} = 1.41 \times 10^{-3} P_{SC} \quad (0.009 \text{ mm.} < P_{SC} < 0.10 \text{ mm.}) \quad (23)$$

so that the total scattering section pressure of

helium when gas is present in both the arc section and scattering chamber is

$$P_{SS} = 6.11 \times 10^{-4} P_{AS} + 1.41 \times 10^{-3} P_{SC}. \quad (24)$$

As previously indicated, the reference intensity measurement (when gas is not admitted to the scattering chamber) is accompanied by weak scattering of the beam through the distance from the atom gun exit to the detector, 6.103 cm., due to pressure P_{SS}^0 as given by Equation (22). When gas is admitted to the scattering chamber, the scattering of the beam is no longer uniform due to the large difference in pressure existing inside the scattering chamber in comparison with that outside. Rosin and Rabi¹⁵ have shown that this type of non-uniform scattering may be treated by resolving it into component parts which, in the present case, may be characterized as follows:

1. Scattering from the atom gun exit to the scattering chamber entrance through 3.863 cm. of gas at pressure P_{SS} as given by Equation (24).

2. Scattering in the cloud (cloud 1) formed by gas escaping from the entrance hole of the scattering chamber.

3. Scattering in the circular entrance channel (0.051 cm. diameter, 0.079 cm. long) of the scattering chamber.

4. Scattering in the scattering chamber proper, a distance of 0.427 cm. from the rear of the entrance hole to the slit jaws. (The area of the slot above the jaws is sufficiently large and its length parallel to the beam axis sufficiently short, to render negligible pressure drops occurring in it when the slit jaws are in position.

5. Scattering in the exit slit which is actually a short, narrow rectangular channel. That the slit has significant length is due to the fact that the defining jaws do not have perfect knife edges. The cross sectional area of the channel is that of a rectangle, 1.00 cm. by 0.0025 cm., and its length is estimated to be 0.01 cm.

6. Scattering in the cloud (cloud 2) formed by gas escaping from the exit slit of the scattering chamber.

7. Scattering from the scattering chamber exit slit to the detector through 1.734 cm. of gas at pressure P_{SS} as given by Equation (24).

The pressure distribution in the circular cross section entrance channel of the scattering chamber may be computed from formulas and tables given by Clausing²¹ for the free molecule flow of

gases through a variety of openings. As gas flows outward from the scattering chamber through this channel toward the atom gun, the pressure drops linearly in the 0.079 cm. length from $0.79P_{SC}$ on the inner side to $0.21P_{SC}$ on the outer side so that the average pressure in the channel is $0.50P_{SC}$. An exact method for calculating the pressure distribution in the cloud at the entrance channel of the scattering chamber does not seem to exist. Fortunately, the scattering in the cloud is a small fraction of the total and very approximate estimates are sufficient. The assumption of Rosin and Rabi, that the pressure in the cloud at its origin is half the pressure at the end of the channel, will be taken as the starting point. In the present case, this leads to an origin value of $0.105P_{SC}$. Since most of the scattering of the beam will be confined to very small angles, the inverse square intensity law, which is a special case of the cosine law of molecular effusion, will be used to estimate pressures in the cloud at distances large in comparison with the channel radius. This leads to

$$P_1(r) = 0.21P_{SC}(0.0255/r)^2 \quad (r \gg 0.0255 \text{ cm.}) \quad (25)$$

where $P_1(r)$ is the pressure in cloud 1 at a distance of r cm. from its origin. Equation (25) shows that the pressure in the cloud 0.310 cm. from its source has already been reduced to a value indistinguishable from the increase in scattering section pressure due to gas in the scattering chamber, namely, $1.41 \times 10^{-3}P_{SC}$. The variation of pressure in cloud 1 over the entire 0.310 cm. distance is adequately represented by the empirical relation

$$P_1(r) = 0.105P_{SC} \exp(-13.9r) \quad (26)$$

* As gas flows outward from the scattering chamber through the rectangular cross section exit slit toward the detector, the pressure drops linearly in the 0.01 cm. length from $0.80P_{SC}$ on the inner side to $0.20P_{SC}$ on the outer side, so that the average pressure in the short channel is $0.50P_{SC}$. In analogy with the procedure used for cloud 1, the pressure at the origin of the cloud emanating from the exit slit, cloud 2, will be taken as $0.10P_{SC}$ and the pressure at distances large compared with the longest beam dimension (about 0.05 cm.) will be computed from

$$P_2(r) = 0.20P_{SC} [0.0025/(\pi r^2)]. \quad (27)$$

Equation (27) predicts that the pressure in cloud 2 will reach the background value of $1.41 \times 10^{-3}P_{SC}$ at $r = 0.336$ cm. The empirical relation

²¹ P. Clausing, *Physica* 9, 65 (1929).

which adequately represents the pressure distribution in the cloud over the entire 0.336 cm. distance is

$$P_2(r) = 0.100P_{SC} \exp(-12.7r). \quad (28)$$

Equation (21) may now be converted into a form applicable to the present scattering situation by rewriting it as

$$I_1/I_2 = \exp \left[- (273/L_v) (\sum x_i P_i / T_1 - 3.73 \times 10^{-3} P_{AS} / T_2) \right] \quad (29)$$

where L_v must be expressed in cm. and where $\sum x_i P_i$ is the sum of the effective values of $x_i P_i$ for the seven component parts which constitute the total scattered beam when gas is admitted to the scattering chamber. In detail

$$\begin{aligned} \sum x_i P_i = & 3.863 P_{SS} + \int_0^{0.310} P_1(r) dr \\ & + 0.079 \times 0.50 P_{SC} + 0.427 P_{SC} \\ & + 0.01 \times 0.50 P_{SC} + \int_0^{0.336} P_2(r) dr + 1.734 P_{SS} \end{aligned} \quad (30)$$

which, upon evaluating the integrals and eliminating P_{SS} through Equation (24), simplifies to

$$\sum x_i P_i = 3.42 \times 10^{-3} P_{AS} + 0.495 P_{SC}. \quad (31)$$

The term $0.495 P_{SC}$ in Equation (31) represents the total scattering contribution of the gas which is admitted to the scattering chamber. The scattering in both clouds contributed but 3 per cent to this total.

Equations (29) and (31) may be combined to give an equation from which L_v may be calculated from experimentally observable quantities, namely,

$$I_1/I_2 = \exp \left[- (273/L_v) (3.42 \times 10^{-3} P_{AS} / T_1 + 0.495 P_{SC} / T_1 - 3.73 \times 10^{-3} P_{AS} / T_2) \right]. \quad (32)$$

In practice, $3.73 \times 10^{-3} P_{AS}$ is not likely to exceed 0.0015 (corresponding to a probable maximum arc pressure of 0.4 mm.) and $0.495 P_{SC}$ is not likely to fall below 0.004 (corresponding to a probable minimum scattering chamber pressure of 0.008 mm.). Since T_1 and T_2 will seldom differ by more than one or two degrees, the ratio of $| 3.42 \times 10^{-3} P_{AS} / T_1 - 3.73 \times 10^{-3} P_{AS} / T_2 |$ to $0.495 P_{SC} / T_2$ will be about 1 : 32 in the most unfavorable case and $(3.42 \times 10^{-3} P_{AS} / T_1 - 3.73 \times 10^{-3} P_{AS} / T_2)$ may be replaced by $- 3.1 \times 10^{-4} P_{AS} / T_1$ with insignificant loss in accuracy so that Equation (32) may be simplified to

$$I_1/I_2 = \exp \left[- 135 (P_{SC} - 6.3 \times 10^{-4} P_{AS}) / (L_v T_1) \right]. \quad (33)$$

It must be remembered that Equation (33) applies only if the following conditions are satisfied:

1. Measurement of the reference intensity, I_2 , must be made with no gas admitted to the scattering chamber.
2. T_1 must be approximately equal to T_2 .
3. P_{SC} must not be appreciably less than 0.008 mm.
4. P_{AS} must not be appreciably greater than 0.4 mm. Conditions 2, 3, and 4 will usually be automatically fulfilled because of present apparatus characteristics. In the event that condition 1 is not fulfilled, it is possible to modify Equation (33) to correspond to specific operating conditions. For example, if an experiment were conducted under the following conditions:

1. Scattered intensity, I_1 , at scattering chamber pressure P_{1SC} and temperature T_1 ,
 2. Reference intensity, I_2 , at scattering chamber pressure P_{2SC} and temperature T_2 ,
 3. T_1 approximately equal to T_2 ,
 4. Arc section pressure, P_{AS} , unchanged during measurement of I_1 and I_2 ,
- the appropriate equation for estimating L_v would be

$$I_1/I_2 = \exp \left[- (135/L_v) (P_{1SC}/T_1 - P_{2SC}/T_2) \right]. \quad (34)$$

Although the pressures in Equations (33) and (34) may be expressed in any convenient units, it is customary to use millimeters of mercury, in which case L_v is the mean free path in cm. at 1 mm. pressure and 273° K. For the present type of scattering system, the cross section, S_v , corresponding to L_v is given by

$$S_v = 1/(nL_v) \quad (35)$$

where n is the number of scattering particles, 3.54×10^{16} , per cc. at 1 mm. and 273° K. if L_v is in cm. at 1 mm. and 273° K. Equations (33) and (34) may therefore be converted to

$$I_1/I_2 = \exp \left[- 4.78 \times 10^{18} (P_{SC} - 6.3 \times 10^{-4} P_{AS}) S_v / T_1 \right] \quad (36)$$

and

$$I_1/I_2 = \exp \left[- 4.78 \times 10^{18} S_v (P_{1SC}/T_1 - P_{2SC}/T_2) \right] \quad (37)$$

respectively, for calculating S_v in cm.² from pressures expressed in mm.

e. Preliminary Scattering Results

Preliminary scattering measurements for helium in helium have been made for atom gun

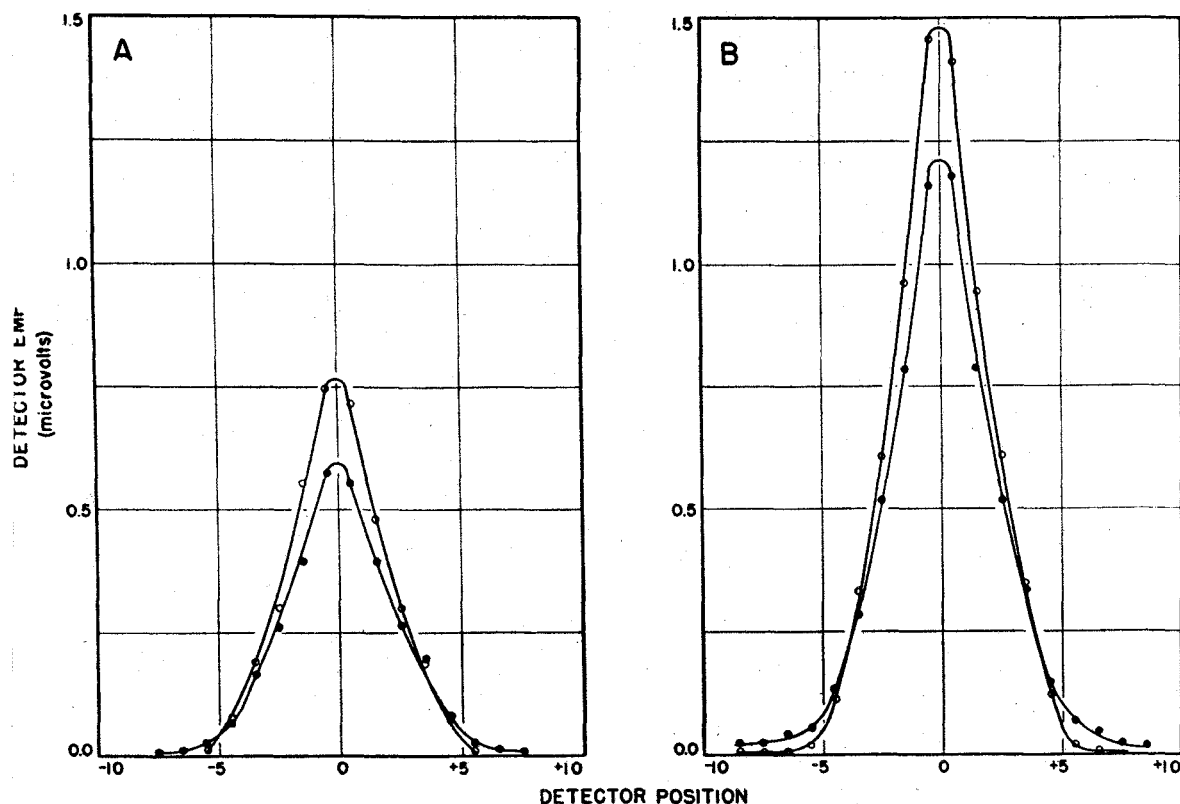


FIGURE 5. Scattering of helium in helium. (Reference beam—○; scattered beam—●) A, 1000 volt beam; B, 1200 volt beam.

voltages in the range 600–1200 volts. In every case the scattered and reference beams were probed in the transverse direction in steps of 0.001" to obtain profiles showing the angular intensity distribution. All reference intensity measurements were made with no gas admitted to the scattering chamber. Typical results for 1000 and 1200 volts (atom gun currents, 3.24 ma. and 3.65 ma., respectively) are shown in Figure 5 where the abscissa is the transverse position of the detector (in thousandths of an inch) relative to the point of maximum intensity. The arc characteristics were the same for both sets of measurements, namely: pressure—0.27 mm.; filament—7.3 amp., 4.40 volts; anode—0.82 amp., 41 volts; cathode—0.24 amp., 160 volts. Similarly, the pressure, P_{sc} , and temperature, T_1 ,

of the helium in the scattering chamber were the same in both sets, 0.0165 mm., and 281.7° K. The temperature, T_2 , of the very low pressure gas in the scattering section during measurement of reference intensities was also 281.7° K.

If a true point detector were used to probe the intensity of the beam, because of the circular cross section of the scattering chamber entrance channel, the transverse and longitudinal profiles of the beam would be the same within the average angular limit, about 7 degrees, determined by the geometry of the exit slit. However, the detector used to obtain the results in Figure 5 has an effective exposed area of a rectangle 0.0014 cm. wide and 0.051 cm. long. Since the long dimension is parallel to the length of the exit slit, transverse motion is essential to obtain

measurements under aperture conditions (1.21 minutes) determined by the 0.0014 cm. dimension.

The curves of Figure 5 show that the resolution of the detector is sufficiently high to obtain a precise pattern of the angular distribution of beam intensity in the very narrow range of angle to which most of the scattering is confined. For example, at both 1000 and 1200 volts, about 90 per cent of the total reference beam intensity is confined to $\pm 0.0035''$ of detector travel with respect to the maximum, corresponding to a symmetrical angular spread of 15.4 minutes about the beam axis. After scattering through 0.0165 mm. of helium, about 75 per cent of the total reference beam intensity is retained in this same region at both voltages.

By using ratios of peak intensities, it is possible to calculate L_v and S_v at 1000 and 1200 volts from Equations (33) and (36) and the values obtained are characteristic of the aperture determined by the width of the detector. If, instead of peak intensities, areas under the curves are used, mean free paths and cross sections are obtained which are characteristic of larger apertures determined by the abscissas which bound the areas. Thus, the use of a single movable detector of sufficiently small aperture can be used to obtain total collision scattering information characteristic, either of its own aperture, or of a series of detectors of larger aperture. This procedure is illustrated by the results in Table IV which compares values of L_v and S_v calculated from peak intensities with those calculated from areas corresponding to $\pm 0.0035''$ of detector travel.

TABLE IV
EFFECT OF APERTURE ON L_v AND S_v

Voltage	Peak Intensities		Integrated Intensities	
	1000	1200	1000	1200
I_1/I_2	0.778	0.818	0.801	0.833
Aperture, min.	1.21	1.21	15.4	15.4
L_v , cm. (at 1 mm. and 273° K.)	0.0312	0.0390	0.0353	0.0428
S_v , 10^{-16} cm. ²	9.06	7.24	8.00	6.60

Although extended measurements on the scattering of high velocity neutral helium atoms are contemplated, the preliminary typical results of Table IV, coupled with previous collision cross section measurements of Amdur and Pearlman,¹² indicate that the present apparatus is capable of supplying quantum mechanical cross sections corresponding to the limit of zero aperture. For example, at 1000 volts, the previously determined

value of S_v was 0.9×10^{-16} cm.² at an average aperture of 2.25 degrees. When this aperture is reduced by about 9 fold, to 15.4 minutes, a correspondingly large increase (about 9 fold) in S_v results and a value of 8.00×10^{-16} cm.² is obtained. Massey and Mohr¹³ have shown, on theoretical grounds, that a large increase in total cross section should occur as the aperture is decreased from large values where the scattering is classical, to small values where diffraction arising from the de Broglie wave character of the scattering system produces extremely high intensity small angle scattering. They further show that the cross section should approach a finite limit as the aperture approaches zero, instead of increasing indefinitely as predicted by classical theory. The results of Table IV confirm the existence of this limit, since a further decrease in aperture of approximately 13 fold (from 15.4 min. to 1.21 min.) merely increases S_v by 13 per cent, from 8.00×10^{-16} cm.² to 9.05×10^{-16} cm.² In general, it is felt that the character of the curves in Figure 5 (high symmetry and overall small scattering of points) and the results of Table IV confirm the expectation that the present apparatus will be capable of supplying scattering results for high velocity beams of the same high quality as those obtained by Mais¹⁴ and by Rosin and Rabi¹⁵ for thermal velocity beams of alkali metals.

D. SUMMARY

An apparatus has been described for producing and scattering high velocity neutral particle beams with energies of 200 to 2000 electron volts. Special features of the apparatus include the use of detectors with small angular apertures, as low as 28.9 seconds of arc, isolation of the scattering gas in a small fraction of the distance between beam source and detector in order to define the angular aperture more sharply, and facilities for accurately probing the beam to obtain measurements of intensity as a function of angle. Extended tests of the apparatus have been made and performance characteristics of vital sections have been given to illustrate the quality of control of which the apparatus is capable and the range of variables which can be covered. Typical preliminary results for 1000 and 1200 volt helium atoms scattered in helium have been presented and analyzed. It is concluded that the present apparatus is capable of supplying scattering information of the same high quality as that available for thermal velocity beams.

E. ACKNOWLEDGMENTS

The authors wish to express their thanks to Professor F. G. Keyes for his continued interest and encouragement during the entire period of the research; to Mr. K. Wilhelmson for aid in constructing the apparatus; and to Mr. L. O.

Mitchell for aid in improving and testing the apparatus.

The authors are deeply indebted to the American Academy of Arts and Sciences which has generously supported the work with grants-in-aid from the Cyrus M. Warren Fund and the Permanent Science Fund.

Proceedings of the American Academy of Arts and Sciences

VOL. 76, No. 4, P. 121-157—OCTOBER, 1948

**RECORDS OF MEETINGS
FROM OCTOBER 1944 TO MAY 1948**

American Academy of Arts and Sciences
OFFICERS AND COMMITTEES FOR 1948-1949

President

HOWARD MUMFORD JONES

Vice-Presidents

Class I

ROLAND G. D. RICHARDSON

Class II

IRVING W. BAILEY

Class III

ROBERT B. STEWART

Class IV

DONALD SCOTT

Secretary

JOHN W. M. BUNKER

Treasurer

HORACE S. FORD

Librarian

ERNEST H. HUNTRESS

Editor

TAYLOR STARCK

Executive Officer

RALPH W. BURHOE

Councillors

Class I

JOHN H. VAN VLECK
PHILIP FRANKLIN
JOSEPH H. KEENAN
ISADORE AMDUR

Terms expire 1949
Terms expire 1950
Terms expire 1951
Terms expire 1952

Class II

CHARLES H. BLAKE
FREDERICK K. MORRIS
PAUL C. MANGELSDORF
ARLIE V. BOCK

Class III

RALPH E. FREEMAN
CHARLES E. WYZANSKI, JR.
HARVEY H. BUNDY
KEYES DEW. METCALF

Terms expire 1949
Terms expire 1950
Terms expire 1951
Terms expire 1952

Class IV

HARRY A. WOLFSON
JOHN G. BEEBE-CENTER
WILLIAM G. CONSTABLE
CRANE BRINTON

The House Committee

CHESTER M. ALTER, *Chairman*

H. ADDINGTON BRUCE

JOHN B. WILBUR

The Committee on Membership

HOWARD M. JONES, *Chairman, ex officio*

To serve for one year

Class I J. LAWRENCE ONCLEY
Class II CHARLES A. JANEWAY
Class III ROBERT G. CALDWELL
Class IV CURT J. DUCASSE

To serve for two years

GEORGE SCATCHARD
RALPH H. WETMORE
JAMES R. KILLIAN, JR.
W. FREEMAN TWADDELL

The Committee on Meetings

HOWARD M. JONES, *Chairman, ex officio*

JOHN W. M. BUNKER, *ex officio*

BART J. BOK
ARTHUR CLAY COPE

HENRY B. PHILLIPS
ERWIN H. SCHELL

The Committee on Finance

HORACE S. FORD, *Chairman, ex officio*

RALPH E. FREEMAN
JEROME C. HUNSAKER

HENRY P. KENDALL
HENRY L. SHATTUCK

The Auditing Committee

THOMAS H. SANDERS

DONALD S. TUCKER

The Committee on Publication

TAYLOR STARCK, *Chairman, ex officio*

ERNEST H. HUNTRESS
KENNETH B. MURDOCK

KENNETH V. THIMANN
THOMAS NORTH WHITEHEAD

The Permanent Science Fund Committee

JOHN W. M. BUNKER, *Chairman*

KIRK BRYAN
GUSTAVUS J. ESSELEN

A. BAIRD HASTINGS
EDWARD L. MORELAND

JULIUS A. STRATTON
PAYSON S. WILD, JR.

The Rumford Committee

HARLOW SHAPLEY, *Chairman*

PERCY W. BRIDGMAN
ARTHUR C. HARDY

GEORGE R. HARRISON
JOSEPH H. KEENAN

EDWIN H. LAND
FRANCIS O. SCHMITT

The C. M. Warren Committee

FREDERICK G. KEYES, *Chairman*

EDWIN J. COHN
LOUIS F. FIESER

HUDSON HOAGLAND
CHARLES A. KRAUS

AVERY A. MORTON
WALTER C. SCHUMB

The Amory Prize Committee

EDWIN B. WILSON, *Chairman*

WILLIAM B. CASTLE
ROY G. HOSKINS

GREGORY PINCUS
GEORGE W. THORN

GEORGE B. WISLOCKI
S. BURT WOLBACH

RECORDS OF MEETINGS

One Thousand Two Hundred and Ninety-Sixth Meeting

OCTOBER 11, 1944—STATED MEETING

The Academy met at its House at 8:30 P. M.
The President in the Chair.

There were present fifty-nine Fellows and twenty guests.

The records of the meeting of May 10 were read and approved.

The Corresponding Secretary reported the receipt of letters accepting Fellowship from the following: Isadore Amdur, Adolf Augustus Berle, Jr., Douglass Vincent Brown, William Bell Dinsmoor, Henry Grattan Doyle, Maxwell Finland, Carl J. Friedrich, Raymond Blaine Fosdick, Paul Rupert Gast, Walter Gropius, Arthur Robert von Hippel, Ernest Martin Hopkins, Columbus O'Donnell Iselin, James Rhyne Killian, Jr., Ronold Wyeth Percival King, Clyde Kay Maben Kluckhohn, Eugene Markley Landis, Ambrose Lansing, Elias Avery Lowe, Saunders MacLane, William Malumud, Richard von Mises, Charles Rufus Morey, John von Neumann, Linus Carl Pauling, Hugh Miller Raup, Albert Charles Smith, Harald Ulrik Sverdrup, Karl Terzaghi, George Widmer Thorn, La Rue Van Hook, Karl Vietor, Sarah Wambaugh, Edgar Bright Wilson, Jr., Charles Edward Wilson, Herbert Eustis Winlock; and from Amado Alonso, Ezequiel Ordoñez, and Daniel Cosío Villegas accepting Foreign Honorary Membership; also letters declining Fellowship from Vera Micheles Dean and Leverett Saltonstall.

He also reported the receipt of a letter from Melvin T. Copeland resigning Fellowship.

The Corresponding Secretary reported that the Council had accepted the Report of the Committee of the Permanent Science Fund in which four grants in aid had been made:

1. To Charles A. Berger, Professor of Cytology and Head of Biology Department, Fordham University, for assistance in continuing studies of the effect of nutrients upon Chromosomes, \$500.

2. To T. T. Chen, Lecturer in Zoology, University of California, Los Angeles, for assistance

in further studies on Cytogenetics of Protozoa, \$250.

3. To C. T. Hurst, Director of Museum, Western State College of Colorado, for assistance and necessary travel in expanding his archaeological explorations in Colorado, \$300.

4. To J. Schiller, Fearing Research Laboratory, Free Hospital for Women, Boston, for expendable materials and assistance in studies on steroid hormones, \$500.

After the introduction of new Fellows, the following communication was presented:

Howard Mumford Jones: *The American Academy: its Status and Prospects.*

The following papers by P. W. Bridgman were read by title: *The Compression of 61 Solid Substances to 25,000 kg/cm², Determined by a New Rapid Method; The Compression of Twenty-one Halogen Compounds and Eleven Other Simple Substances to 100,000 kg/cm².*

The meeting was dissolved at 9:50 P. M.

One Thousand Two Hundred and Ninety-seventh Meeting

NOVEMBER 8, 1944—STATED MEETING

The Academy met at its House at 8:20 P. M.
The President in the Chair.

There were sixty-two Fellows and thirty-one guests present.

The records of the meeting of October 11 were read and approved.

The Corresponding Secretary announced that the President had been authorized to appoint a commission of five Fellows to study the functions of the Academy.

The Corresponding Secretary reported that Reid Hunt and Archibald T. Davison have been transferred to the status of Fellows Emeriti.

Frederick H. Pratt called attention to E. L. Mark's sixtieth anniversary as a Fellow and stated that the Council had voted to send him a note of congratulation.

After the introduction of new Fellows the following communications were presented:

Edwin J. Cohn: *Blood Is a Very Special Juice.*

Charles A. Janeway: *The Use of Blood and Blood Derivatives in Medicine.*

Franc D. Ingraham: *The Use of Blood Derivatives in Surgery*.

The meeting was dissolved at 10:25 P. M.

One Thousand Two Hundred and Ninety-eighth Meeting

DECEMBER 13, 1944.—STATED MEETING

The Academy met at its House at 8:25 P. M.

The President in the Chair.

This meeting had been designated as Ladies' Night, and there were present more than two hundred and fifty Fellows and guests.

The records of the meeting of November 8 were read and approved.

The following communication was presented:

Francis Henry Taylor: *The Problem of Salvage and Restitution of the Artistic Treasures of Europe*.

An exhibit, *Quartz Goes to War*, was on view in the office, Mr. Ernest R. Bohro, of the August E. Miller Laboratories, being the demonstrator.

The meeting was dissolved at 9:40 P. M.

One Thousand Two Hundred and Ninety-ninth Meeting

JANUARY 10, 1945.—STATED MEETING

The Academy met at its House at 8:20 P. M.

The President in the Chair.

There were present twenty-nine Fellows and fourteen guests.

The records of the meeting of December 13 were read and approved.

The Corresponding Secretary announced that the Council had appointed Harlow Shapley as Chairman of the Rumford Committee in place of the late Norton A. Kent.

The President announced that the Boston Institute for Religious and Social Studies will hold meetings at the house of the Academy on eight successive Tuesdays, beginning January 23.

The following communication was presented:

Karl Terzaghi: *Soil Mechanics*.

There was an exhibit of *Some Early New England Refractories used by Paul Revere in his Smelter at Norton, Mass.*, arranged by Professor Frederick H. Norton, of the Massachusetts Institute of Technology.

The meeting was dissolved at 10:15 P. M.

One Thousand and Three Hundredth Meeting

FEBRUARY 14, 1945.—STATED MEETING

The Academy met at its House at 8:20 P. M.

The President in the Chair.

There were present twenty-three Fellows and eighteen guests.

In the absence of the Recording Secretary his duties were performed by the Corresponding Secretary.

The records of the meeting of January 10 were read and approved.

The following communication was presented:

William Malamud: *A Psychiatric Approach to the Problem of Veteran Readjustment*.

An exhibit of material concerning Massachusetts veterans in former wars was arranged through the courtesy of the Harvard College Library.

The meeting was dissolved at 9:45 P. M.

One Thousand Three Hundred and First Meeting

MARCH 14, 1945.—STATED MEETING

The Academy met at its House at 8:25 P. M.

Vice-President Robinson in the Chair.

There were present forty-two Fellows and eighteen guests.

The records of the meeting of February 14 were read and approved.

It was announced that the President had appointed a Nominating Committee, as follows: Bart J. Bok, of Class I; Frederick K. Morris, of Class II, *Chairman*; Charles E. Wyzanski, Jr., of Class III; Leonard Carmichael, of Class IV.

Announcement was also made of the appointment of a Committee to study the structure and operation of the Academy, in accordance with a vote of the Council last November. This Committee, which has already held two meetings, consists at present of four members: Kirtley F. Mather, *Chairman*, Curt J. Ducasse, John W. M. Bunker, and Leonard Carmichael.

On the recommendation of the Council the following appropriations were voted for the year 1945-1946:

From the income of the General Fund, \$7,800, to be used as follows:

for House expenses	\$2,600
for General and meeting expenses	1,000
for Library expenses	3,000
for Treasurer's expenses	1,200
Total	\$7,800

From the income of the Publication Funds, \$2,400, to be used for publication.

From the income of the Rumford Fund, \$3,370, to be used at the discretion of the Committee.

From the income of the C. M. Warren Committee, \$1,000, to be used at the discretion of the Committee.

The following communication was presented:

Douglas Bush: *The Humanities and Science in Education in the Seventeenth and Twentieth Centuries*.

There was an exhibit of famous Renaissance treatises, loaned by the Houghton Library of Harvard University.

The meeting was dissolved at 9:45 P. M.

One Thousand Three Hundred and Second Meeting

APRIL 11, 1945.—STATED MEETING

The Academy met at its House at 8:27 P. M.

The President in the Chair.

There were present thirty-one Fellows and sixteen guests.

In the absence of the Recording Secretary, his duties were performed by the Corresponding Secretary.

The records of the meeting of March 14 were read and approved.

It was announced that an amendment to the Statutes establishing the Committee on the Permanent Science Fund as a standing committee will be submitted to the Academy for action at its meeting on May 9.

Announcement was made of the proposed Regulations for the Conference of Secretaries of the American Council of Learned Societies. Approval of these regulations will be requested at the next Academy meeting.

The following communication was presented:

Henry Allen Moe: *The Selection of Persons for Research Fellowships*.

The meeting was dissolved at 9:42 P. M.

One Thousand Three Hundred and Third Meeting

MAY 9, 1945.—ANNUAL MEETING

The Academy met at its House at 8:20 P. M.

The President in the Chair.

There were present forty-four Fellows and nine guests.

The records of the meeting of April 11 were read and approved.

The following reports were presented:

REPORT OF THE COUNCIL

Since the last report of the Council there have been reported the deaths of seventeen Fellows: George David Birkhoff, Alexis Carrel, George Whiteley Coggeshall, Alfred Victor de Forest, Edmund Burke Delabarre, Carl Engel, Frederic Harold Fay, James Ford, Philip Fox, Roy Kenneth Hack, William Henry Howell, Walter Louis Jennings, Norton Adams Kent, Charles Francis Park, Robert Hallowell Richards, Frederick Slocum, William Trelease; and nine Foreign Honorary Members: Rt. Hon. James Richard Atkin, Sir Thomas Barlow, Godfrey Rathbone Benson, Baron Charnwood, Gustav Cassel, Sir Arthur Stanley Eddington, Sir William Napier Shaw, Aurel Stodola, Peter B. Struve. Three Fellows have resigned: Melvin Thomas Copeland, William Leonard Crum, Alan Richards Moritz.

Twelve names have been added to the list of Fellows Emeriti: Walter Bradford Cannon, Charles Townsend Copeland, Archibald Thompson Davison, Richmond Laurin Hawkins, Frank Lauren Hitchcock, Reid Hunt, Charles Palache, Walter Raymond Spalding, Clair Elsmere Turner, Alfred North Whitehead, Edmund Allen Whitman, Frederick Shenstone Woods.

Thirty-nine Fellows and four Foreign Honorary Members were elected by the Council and announced to the Academy in May, 1944. All of these have accepted their election with two exceptions—Vera Micheles Dean and Leverett Saltonstall—who declined.

The roll now includes 767 Fellows, 17 Fellows Emeriti, and 113 Foreign Honorary Members (not including those elected in May, 1945).

REPORT OF THE TREASURER

(Extract)

In the absence of the Treasurer, his report was read by the Corresponding Secretary. A summary of the receipts and expenditures follows:

*RECEIPTS, 1944-1945

Academy, General:

From: Investment Income	\$13,849.82	
Less: Income to Special Funds	10,972.73	
		\$2,877.09
Assessments and Admission Fees	4,250.00	
		\$7,127.09

Amory Prize Committee:

From: Investment Income..... 3,352.27

Publications Committee:

From: Investment Income...	\$2,303.04	
Sale of Publications.....	722.39	
Lake Publication, Subscriptions.....	182.80	
		3,208.23

*Excluding sales of securities.

<i>Rumford Committee:</i>	
From: Investment Income.....	3,255.41
<i>C. M. Warren Committee:</i>	
From: Investment Income.....	988.35
<i>Mabel S. Agassiz Fund:</i>	
From: Investment Income.....	107.40
<i>Permanent Science Fund:</i>	
From: Boston Safe Deposit and Trust Co., Trustee.....	\$10,820.19
Investment Income.....	898.23
	11,718.42
<i>Kennelly Fund:</i>	
From: Investment Income.....	68.03
<i>Total Receipts</i>	\$29,825.20

*EXPENDITURES, 1944-1945

<i>Academy, General:</i>	
Library, Salaries..	\$2,432.00
Books and Binding	764.79
	\$3,196.79
General (Net).....	1,062.87
House (Net).....	2,600.13
Treasurer's Office.....	599.94
Insurance.....	578.25
	\$8,037.98
<i>Amory Prize Committee</i>	
Expense.....	43.75
<i>Publications Committee:</i>	
General.....	\$604.81
Lake.....	13.00
	617.81
<i>C. M. Warren Committee:</i>	
Grants.....	\$540.00
Transfer of Income to Fund..	1,000.00
	1,540.00
<i>Mabel S. Agassiz Fund:</i>	
For Meetings.....	107.40
<i>Permanent Science Fund:</i>	
Grants.....	2,280.00
<i>Total Expenditures</i>	\$12,626.94

REPORT OF THE RUMFORD COMMITTEE

On behalf of the Rumford Fund Committee of the American Academy of Arts and Sciences, I report that during the past year there have been no applications for grants-in-aid received by the Committee.

In view of the current security regulations which prevent our knowing fully of important contributions of the past few years in the fields of heat and light, the Rumford Fund Committee has decided not to recommend candidates for the Rumford Medals.

The Treasurer reports the total funds available for the work of the Committee on March 12, 1945, is

*Excluding purchases of securities.

\$10,113.84, and that the estimated income for 1945-1946 is \$3,370.

Respectfully submitted,

HARLOW SHAPLEY, *Chairman*

May 9, 1945

REPORT OF THE CYRUS M. WARREN COMMITTEE

The Committee had available for grants during the fiscal year 1944-1945 a total sum of \$1,669.53, of which \$870.00 was appropriated at the March, 1944 meeting and \$799.53 remained as a balance from the previous year. It was considered advisable, and so voted by the Committee, to return \$1,000.00 to the principal. Grants were made totalling \$390.00, as follows:

To Doctor Ralph N. Prince of the University of New Hampshire, a grant of \$200.00 for materials to construct apparatus in connection with a project to develop an optical means of determining the purity of cellulosic materials.

To Professor Pierre Van Rysselberghe of the University of Oregon, a grant of \$190.00 for the purchase of a Leeds and Northrup audio frequency oscillator for use in the determination of the conductances of non-aqueous solutions of metallic salts, particularly those of magnesium and aluminum.

A further report was received from Professor Thomas W. Davis of New York University in regard to his grant of the preceding year. After considerable delay he was able to secure a suitable fractionating column for which the grant was awarded.

Respectfully submitted,

FREDERICK G. KEYES, *Chairman*

May 9, 1945

REPORT OF THE COMMITTEE OF PUBLICATION

The Publication Committee has held no regular meetings this year, business having been transacted by consultation and correspondence. Three numbers of the *Proceedings* have been published:

VOLUME 75

5. Barnett, S. J. *New Researches on Magnetization by Rotation and the Gyromagnetic Ratios of Ferromagnetic Substances.* pp. 109-129. August, 1944.

6. *Presidential Address; Records of Meetings; Biographical Notices; Presidents of the Academy; Officers and Committees; List of Fellows and Foreign Honorary Members, etc.;* pp. 131-208. December, 1944.

VOLUME 76

1. Bridgman, P. W. *The Compression of Twenty-one Halogen Compounds and Eleven Other Simple Substances to 100,000 kg/cm²; the Compression of Sixty-one Solid Substances to 25,000 kg/cm², Determined by a New Rapid Method.* pp. 1-24. February, 1945.

The Index to Professor and Mrs. Lake's *Dated Greek Minuscule Manuscripts to the year 1200* has been en-

tirely printed off and is being bound. It forms a monograph of smaller format than the plates—about 200 pages. It seemed wise to print a larger number of these as there will be individual sales for it in addition to those to subscribers to the series.

Professor Hatch's *Dated Syriac Manuscripts* is in corrected page proof, but has not, at last reports, been printed off. There are no other papers on the roster for publication.

Respectfully submitted,
ROBERT P. BLAKE, *Chairman*

May 9, 1945

REPORT OF THE LIBRARY COMMITTEE

During the year, 111 bound volumes (mainly of serials) were added to the library, making a total of 47,372 now on the shelves. Of this number 97 were received by gift or exchange and 14, or only 8 per cent, were purchased. The appropriation was \$2,625 for the year ending March 31, 1945. Expenditures were as follows:

Salaries.....	\$2,432.00
Purchase of books and periodicals.....	522.54
Binding and repairing.....	242.25

Total..... \$3,196.79

In addition to the use of books in the building, 57 books and pamphlets were borrowed by 5 Fellows and 19 libraries.

Thus reads, in general, the gist of annual reports varying little within the present century, in the earlier years of which the Academy ceased adding to its book collection, concentrated upon its periodical files—and made almost negligible use of either. Yet the library, a terra incognita to most of our Fellows, has been in a sense the integrating symbol of the Academy as generations have passed. Our shelves still hold the books of eighteenth-century founders; and accessions of the nineteenth-century form a unique record of the scientific and humanistic interests of the Academy throughout that period. Since then, the principal growth has been in periodical files, so that now the stacks groan with memoirs and transactions from every intellectual quarter of the globe.

A recent inspection of the shelves kindly undertaken by a group of expert librarians has emphasized the potential value of our unexploited resources. At the same time the opinion was expressed that these resources can be made useful only in so far as they are selectively dispersed to areas which lack, rather than duplicate the material. Your Committee are not in sufficient agreement to render concerted opinion; but the facts should be understood by all.

To our great misfortune, the extent of appropriation and personnel allotted to the upkeep of the collection has for many years been insufficient to cope with a growth which now nears the 50,000-volume mark. The library has had throughout not only to shoulder the highly detailed work of the general secretariat, but to

carry it under the library appropriation. This means that there can be no strictly full-time staff service, and no provision for the conservation of library property except through part-time janitorial effort. It means above all an undue demand upon the Assistant Librarian, whose executive duties greatly limit the exercise of her technical library training and experience.

The librarian of an earlier generation, in reporting the inability of one person to handle both library and general Academy business, took occasion to note the "crumbling away" of the old bindings. Seven years later, in 1913, his successor estimated that, in the new building, overcrowding was provided against for fifteen years. Now, after thirty years' growth, the congestion is deplorable and "crumbling" unabated; with no relief in sight other than drastic dismemberment applied to all but historic treasures, the salvage of which is already proving a long and expensive process.

Hence from more than one direction we are impelled toward some form of radical action. Nevertheless, to those who know our library it has a strong utilitarian as well as antiquarian appeal. To these it continues to prove an invaluable resource, containing as it does many long and rare files and offering to Fellows certain privileges of withdrawal unapproached in their liberality. Your Committee invite examination of the stacks and urge full consideration of the situation. It is one of the major problems now before us.

Respectfully submitted,
FREDERICK H. PRATT, *Chairman*

May 9, 1945

REPORT OF THE HOUSE COMMITTEE

During the year ending March 31, 1945, the House Committee has had at its disposal funds amounting to \$2,852.69, as follows:

Appropriation for 1944-1945.....	\$2,600.00
Received from other societies for the use of House facilities.....	252.69
Total.....	\$2,852.69

The expenditures amounted to \$2,852.92. Of this sum \$2,699.83 was spent for the routine expenses, janitor, heat, light, telephone, etc., and \$153.09 for the upkeep of the building.

Meetings have been held as follows:

The Academy.....	8
American Council of Learned Societies.....	3
Archaeological Institute of America, Boston Chapter	1
Boston Surgical Society.....	3
Institute for Religious and Social Studies.....	8
New England Botanical Club.....	9
Pan-American Society of Massachusetts.....	10
United China Relief.....	4
Total.....	46

The Council Chamber has been used for the Academy Council and Committee meetings, and also by the

Trustees of the Children's Museum and the New England Farm and Garden Association.

A detailed list of the expenditures follows:

Janitor.....	\$1,001.00
Fuel.....	1,013.58
Electricity: Light.....	197.73
Power.....	46.28
Elevator service and repairs.....	134.24
Telephone.....	155.96
Gas.....	54.90
Water.....	64.40
Upkeep of building.....	153.09
Janitor's supplies and sundries.....	31.74
Total	<u>\$2,852.92</u>

The Academy received during the year by gift from Mrs. Maximilian Agassiz portraits of Louis, Alexander, and Maximilian Agassiz, and a bronze bas-relief of Alexander Agassiz together with a copper plate inscribed with resolutions passed in his memory by the stockholders of the Calumet & Hecla Consolidated Copper Co. These have been hung in the rooms of the Academy. A letter of thanks was sent to Mrs. Agassiz by the Chairman of the House Committee.

Respectfully submitted,

C. M. SPOFFORD, *Chairman*

May 9, 1945

The Corresponding Secretary announced that the following had been elected members of the Academy:

FELLOWS

CLASS I, SECTION 1

Garrett Birkhoff.....Cambridge
Norman Levinson.....Belmont

CLASS I, SECTION 2

Robley Dunglison Evans.....Belmont

CLASS I, SECTION 3

Eric Glendinning Ball.....Newton Highlands
Arthur Clay Cope.....Belmont
John Lawrence Oncley.....Watertown

CLASS I, SECTION 4

Hardy Cross.....New Haven, Conn.
Frederick Emmons Terman.....Belmont
John Benson Wilbur.....Belmont

CLASS II, SECTION I

Martin Julian Buerger.....Lincoln
Henry Crosby Stetson.....Belmont

CLASS II, SECTION 2

Dennis Robert Hoagland.....Berkeley, Calif.
Herman Augustus Spoehr.....Palo Alto, Calif.

CLASS II, SECTION 3

John Robert Looftbourow.....Cambridge
John Henry Welsh, Jr.....Cambridge
Leland Clifton Wyman.....Jamaica Plain

CLASS II, SECTION 4

James Morison Faulkner.....Brookline
Thomas Hale Ham.....Brookline

CLASS III, SECTION 3

Seymour Edwin Harris.....West Acton
William Rupert Maclaurin.....Cambridge
Talcott Parsons.....Belmont
Howard Eugene Wilson.....West Newton

CLASS III, SECTION 4

Edwin Sharp Burdell.....New York, N. Y.
William Lockhart Clayton.....Washington, D. C.
Henry Allen Moe.....New York, N. Y.

CLASS IV, SECTION 1

Edwin Ray Guthrie.....Seattle, Wash.
Charles Lincoln Taylor, Jr.....Cambridge

CLASS IV, SECTION 3

George Wiley Sherburn.....Cambridge
Taylor Starck.....Cambridge

CLASS IV, SECTION 4

Samuel Chamberlain.....Marblehead
William Alexander Jackson.....Cambridge
Keyes DeWitt Metcalf.....Belmont
Martin Wagner.....Cambridge

FOREIGN HONORARY MEMBERS

CLASS I, SECTION 1

Sir Harold Spencer Jones.....Greenwich

CLASS I, SECTION 2

Niels David Bohr.....Copenhagen

CLASS III, SECTION 3

Dennis Holme Robertson.....London

CLASS III, SECTION 4

Alfredo L. Palacios.....Buenos Aires

CLASS IV, SECTION 3

Tomás Navarro Tomás.....Madrid

It was voted to adopt an amendment to the Statutes by inserting in Chapter XI in Article 2 the following paragraph:

The Permanent Science Fund Committee, to consist of seven Fellows, which shall recommend from time to time to the Council all appropriations from the income received by the Academy from the Trustee of the Permanent Science Fund, for effecting the purposes set forth in the Agreement and Declaration of Trust which governs the use of this Fund.

It was voted to approve amendments to the constitution and by-laws of the American Council of Learned Societies, providing for a conference of secretaries at the annual meeting of the Council.

On the recommendation of the Treasurer it was voted that the annual assessment for resident Fellows for the year 1945-1946 be fifteen dollars.

The annual election resulted in the choice of the following officers and committees:

Howard M. Jones *President*
 George R. Harrison *Vice-President for Class I*
 Alfred C. Lane *Vice-President for Class II*
 Ralph E. Flanders *Vice-President for Class III*
 Fred N. Robinson *Vice-President for Class IV*
 Abbott P. Usher *Corresponding Secretary*
 Hudson Hoagland *Recording Secretary*
 Horace S. Ford *Treasurer*
 Frederick H. Pratt *Librarian*
 Robert P. Blake *Editor*

COUNCILLORS FOR FOUR YEARS

John H. Van Vleck Class I
 Charles H. Blake Class II
 Oliver M. W. Sprague Class III
 Harry A. Wolfson Class IV

COMMITTEE ON POLICY AND RESOURCES

For Five Years: W. Cameron Forbes

FINANCE COMMITTEE

Jerome C. Hunsaker Henry P. Kendall
 Ralph E. Freeman John F. Ebersole

RUMFORD COMMITTEE

Harlow Shapley, *Chairman*

Percey W. Bridgman Robert B. Lindsay
 Harry M. Goodwin Francis O. Schmitt
 George R. Harrison Edwin H. Land

C. M. WARREN COMMITTEE

Frederick G. Keyes, *Chairman*

Gregory P. Baxter Avery A. Morton
 Charles A. Kraus Walter C. Schumb
 Grinnell Jones Kenneth L. Mark

COMMITTEE OF PUBLICATION

Robert P. Blake, *Chairman, ex officio*

Edwin C. Kemble Class I
 Ralph H. Wetmore Class II
 Arthur H. Cole Class III
 Robert P. Casey Class IV

COMMITTEE ON THE LIBRARY

Frederick H. Pratt, *Chairman, ex officio*

Raymond C. Archibald Class I
 Thomas Barbour Class II
 Francis N. Balch Class III
 Henry B. Washburn Class IV

AUDITING COMMITTEE

Erwin H. Schell Alexander Forbes

HOUSE COMMITTEE

Charles M. Spofford, *Chairman*

H. Addington Bruce Robert P. Bigelow
 Donald S. Tucker

COMMITTEE ON BIOGRAPHICAL NOTICES

For Three Years

Alfred C. Lane Austin W. Scott

COMMITTEE ON MEETINGS

The President

The Recording Secretary

Leonard Carmichael Jerome D. Greene
 Abbot P. Usher Frederick K. Morris

The following communication was presented:

Joseph P. Hudnut and Carl J. Friedrich: *The Boston Contest.*

The meeting was dissolved at 10:20 P. M.

One Thousand Three Hundred and Fourth Meeting

OCTOBER 10, 1945.—STATED MEETING

The Academy met at the Old South Parish House Building, in Copley Square, at 8:15 P. M., the change of meeting place having been made necessary by repairs to the house of the Academy.

This meeting had been designated as Ladies' Night, and there were present about three hundred Fellows and guests.

The reading of the records of the meeting of May 9 was omitted.

The following communication was presented:

Harlow Shapley: *Report on Soviet Science.*

The meeting was then dissolved.

One Thousand Three Hundred and Fifth Meeting

NOVEMBER 14, 1945.—STATED MEETING

The Academy met at the Old South Parish House Building at 8:22 P. M.

The President in the Chair.

There were present fifty-one Fellows and twenty guests.

The records of the meetings of May 9 and October 10 were read and approved.

It was voted to discontinue the Committee on Policy and Resources (a standing committee), through an amendment to the Statutes, deleting Paragraph ii, Article 2, of Chapter XI.

Professor Robley D. Evans was presented to the Academy by Vice-President George R. Harrison.

The Chairman of the House Committee reported on the progress of the plans for the alteration of the Academy's House.

The President announced that the four Vice-Presidents had been asked to prepare lists of the war work of the Fellows in their Classes, and gave a brief review of the partial returns reported by three of them.

The topic for the evening was *A National Policy for Scientific Research* and it was presented as a symposium by Messrs. Bradley Dewey, Pendleton Herring and Lee A. Du Bridge. The communications were followed by a lively discussion from the floor.

The meeting was dissolved at 10:15 P. M.

One Thousand Three Hundred and Sixth Meeting

DECEMBER 12, 1945.—STATED MEETING

The Academy met at the Old South Parish House Building at 8:25 P. M.

The President in the Chair.

There were present thirty-seven Fellows and fourteen guests.

In the absence of the Recording Secretary, the Corresponding Secretary read the records of the meeting of November 14, which were approved by the Academy.

The Corresponding Secretary reported that the Council had prepared a number of amendments to the Statutes designed to clarify the language of several paragraphs, to define more adequately the powers and duties of the President, and to describe the procedure on amendments that has in fact been followed since the establishment of the Council.

The following communication was presented:

Charles E. Wyzanski, Jr.: *The War Criminal Trials*.

After a stimulating discussion, the meeting was dissolved at 10 P. M.

One Thousand Three Hundred and Seventh Meeting

JANUARY 9, 1946.—STATED MEETING

The Academy met at the Old South Parish House Building at 8:20 P. M.

The President in the Chair.

There were present eighty-four Fellows and thirty-four guests.

The records of the meeting of December 12 were read and approved.

In the absence of the Corresponding Secretary, the Recording Secretary announced that the Council had adopted the following resolution:

Believing that the peace of the world and the advancement of the arts, the sciences, and education in all countries can be effectively furthered by an active

support of the United Nations Educational, Scientific and Cultural Organization, the Council of the American Academy of Arts and Sciences congratulates the Senate and House of Representatives of the Congress of the United States upon the several resolutions adopted by them favoring support of this organization, and urges upon the Congress the desirability of ratifying the charter of the organization on the basis of the signature of our representatives at the London Conference last November.

In order that the widest support may be given to the United Nations Educational, Scientific and Cultural Organization, the Council desires that copies of this resolution shall be sent to all the learned and scientific bodies throughout the world with which it has communication, to the public press, to the President of the United States, the Secretary of State, the Speaker of the House, the President of the Senate, and the Assistant Secretaries of State.

The President announced that instead of the usual stated meeting in April, the Academy would hold a dinner meeting at the Copley Plaza Hotel on April 17.

The following communication was presented:

James Bryant Conant: *Science and the National Welfare*.

The meeting was dissolved at 9:45 P. M.

One Thousand Three Hundred and Eighth Meeting

FEBRUARY 13, 1946.—STATED MEETING

The Academy met at the Old South Parish House Building at 8:20 P. M.

The President in the Chair.

There were present thirty-five Fellows and four guests.

In the absence of the Recording Secretary, the Corresponding Secretary served in his stead.

The records of the meeting of January 9 were read and approved.

Two new Fellows were introduced: William A. Jackson by Vice-President Robinson, and Talcott Parsons by the Corresponding Secretary.

The following amendments to the Statutes recommended by the Council at its January meeting were adopted by the Academy with no dissenting votes:

CHAPTER II, Article 4, shall be amended to read: "If any person, after being notified of his election as Fellow, shall neglect for six months to accept in writing, or if a Fellow resident within fifty miles of Boston shall neglect to pay his Admission Fee *within six months* of his election, his election shall be void; and if any

Fellow resident within fifty miles of Boston shall neglect to pay his Annual Dues for six months after they are due, provided his attention shall have been called to this Article of the Statutes by the *Treasurer* in the meantime, he shall cease to be a Fellow.

A non-resident Fellow, elected since 1938, who neglects to pay his Annual Dues for six months after they are due, and who ignores notification by the Treasurer of the requirement of this Article, shall cease to be a Fellow.

But upon petition by the Fellow or by any officer of the Academy, the Council may by a majority vote suspend the provisions of this Article for any additional period of time not longer than three months."

CHAPTER II, Article 5. First paragraph: Omit the clause: "unless previously as an Associate he has paid an Admission Fee of like amount." Second paragraph, second line: Omit the words "and others may."

CHAPTER IV, Article 1. Paragraph three, third line: Omit "on Resources and Policy" and substitute "on the Permanent Science Fund."

CHAPTER V, Article 1. For "the senior" in the second line, substitute "a." Omit the parenthesis ("seniority to be determined by length of continuous fellowship in the Academy").

Add as a new paragraph:

"The President shall be the chief executive officer of the Academy. He shall present to the Council for its consideration all matters pertinent to the interests of the Academy and to the discharge of its obligations to the community or to the advancement of scholarship. The President shall be Chairman of the Committee on Meetings."

CHAPTER VI, Article 1. Add a paragraph as follows:

"He shall arrange for the preservation of records of the death of Fellows and biographical notices published on the occasion of their death, or at other times. If existing notices are inadequate, he shall arrange for the preparation of a suitable biographical notice to be published in the Proceedings of the Academy or in some professional journal associated with the activities of the deceased Fellow."

CHAPTER VI, Article 2. Last paragraph, first line, substitute "any" for the second "the."

CHAPTER XI. Omit paragraph (ii) as it now stands and substitute the paragraph providing for a standing committee on the Permanent Science Fund, Omit paragraph (x).

CHAPTER XII, Article 7. Omit the present text and substitute the following:

"All amendments to the Statutes, whether proposed by Fellows or by the Council, shall be considered by the Council and reported with recommendations for action to the Academy. At a subsequent Stated Meeting, or at a Special Meeting called for the purpose, the notice for which in either case shall state this proposed amendment, the Academy shall act upon the amendment. Two-thirds of the Fellows present, in a meeting

of not less than twenty-five Fellows, must vote in the affirmative to enact the amendment."

The following communication was presented:

Edward Sagendorph Mason: *The Economic Future of Germany*.

The meeting was dissolved at 9:40 P. M.

One Thousand Three Hundred and Ninth Meeting

MARCH 13, 1946.—STATED MEETING

The Academy met at its House at 8:25 P. M.

The President in the Chair.

There were present forty Fellows and six guests.

The records of the meeting of February 13 were read and approved.

On the recommendation of the Council the following appropriations for the year 1946-1947 were voted:

From the income of the General Fund, \$9,200, to be used as follows:

For House expenses.....	\$3,600
for General and Meeting expenses.....	1,400
for Library expenses: Salaries.....	2,400
Books, Periodicals & Binding	600
for Treasurer's expenses.....	1,200
Total.....	\$9,200

It was also voted that the Editor, the Chairman of the Rumford Committee, and the Chairman of the C. M. Warren Committee be authorized to draw upon the balances available in their respective Funds.

The President announced that he had appointed the following as a Nominating Committee: Bart J. Bok, of Class I, *Chairman*; Ralph H. Wetmore, of Class II; Douglass V. Brown, of Class III; Michael J. Ahern, S. J., of Class IV.

The following communication was presented:

Kenneth V. Thimann: *Growth Hormones in Plants*. This was illustrated by lantern slides and by living material.

The meeting was dissolved at 9:30 P. M.

One Thousand Three Hundred and Tenth Meeting

APRIL 17, 1946.—DINNER MEETING

The first annual dinner meeting of the Academy was held at the Copley Plaza Hotel on Wednesday, April 17, taking the place of the stated meeting on April 10.

One hundred and sixteen members were present, and the speakers were Dr. Waldo G. Leland, of the American Council of Learned Societies, and President Karl T. Compton, of the Massachusetts Institute of Technology.

At the request of the President, Mr. Robert Frost recited several of his poems.

One Thousand Three Hundred and Eleventh Meeting

MAY 8, 1946.—ANNUAL MEETING

The Academy met at its House at 8:20 P. M.
The President in the Chair.

There were present fifty-eight Fellows and eleven guests.

The records of the meetings of March 13 and April 17 were read and approved.

The Corresponding Secretary reported that the Council had voted to recommend to the Academy that the Statutes be amended to provide for the addition of the Amory Prize Committee to the list of standing committees.

He also read a resolution which the Council had adopted, copies of which are to be sent to the President of the United States, the President of the Senate, the Speaker of the House, the Senators from the Commonwealth of Massachusetts, and other academies in the United States of America, as follows:

WHEREAS, whole populations in Europe and Asia face death by hunger if immediate and extensive help is not given them; and

WHEREAS, the loss to the world by starvation of scientists and scholars is of special concern to learned bodies; and

IN SO FAR as the food sent abroad from this country is neither in proportion to what we can spare nor adequate to the crisis,

Resolved, by the Council of the American Academy of Arts and Sciences, that we urge upon our government an increase in the amount of wheat, milk, and fats set aside to meet this emergency as well as an increase in the amount and speed of the transportation accorded this food; and

Resolved, that, voluntary rationing having proved inadequate, we urge a return to consumer rationing to assure both fair distribution of food in this country and adequate supplies for famine relief; and

Resolved, that copies of this resolution be sent to the President of the United States, the President of the Senate, the Speaker of the House, the Senators from the Commonwealth of Massachusetts, and other academies in the United States of America.

The Corresponding Secretary announced that at its meeting on April 30 the Council had made the following grants from the Permanent Science Fund:

1. To Charles F. Brooks, Director, Blue Hill Observatory, Harvard University, for completion of certain studies of cloud systems associated with storms in the eastern United States, \$625.

2. To Gregory Pincus, Director of Laboratories, Worcester Foundation for Experimental Biology, for assistance in a study of hormonal control of lymphocytes, \$1,800.

3. To A. H. Reesor Smith, Lecturer, College of Engineering, University of California, as compensation for assistance contingent upon remaining necessary funds being secured otherwise for the synthesis of vinyl cyclopropane, \$1,800.

4. To George Sachs, Professor of Physical Metallurgy, Case School of Applied Science, Cleveland, as compensation for assistance in the study of properties of thin metallic membranes, \$900.

5. To Irving M. Klotz, Instructor in Chemistry, Northwestern University, for assistance in his study of the interactions of proteins with organic molecules, \$1,300.

The Corresponding Secretary announced that the following had been elected members of the Academy:

FELLOWS

CLASS I, SECTION 1.

James Gilbert Baker.....Waban
John Landes Barnes.....Winchester
Subrahmanyam Chandrasekhar....Williams Bay, Wis.

CLASS I, SECTION 2

Lee Alvin Du Bridge.....Rochester, N. Y.
Julius Adams Stratton.....Belmont

CLASS I, SECTION 3

Paul Doughty Bartlett.....Weston
Walter Hugo Stockmayer.....Weston

CLASS I, SECTION 4

William Loren Batt.....Washington, D. C.
Howard Wilson Emmons.....Sudbury

CLASS II, SECTION 1

Roland Frank Beers.....Lincoln
Cornelius Searle Hurlbut, Jr.....Belmont

CLASS II, SECTION 2

Ralph Erskine Cleland.....Bloomington, Ind.

CLASS II, SECTION 3

George Wells Beadle.....Palo Alto, Calif.
James Lee Peters.....Harvard
Kenneth David Roeder.....Medford

CLASS II, SECTION 4

John Franklin Enders.....Boston
 Charles Alderson Janeway.....Weston
 Siegfried Josef Thannhauser.....Brookline

CLASS III, SECTION 2

Harvey Hollister Bundy.....Boston
 John Sloan Dickey.....Hanover, N. H.
 Robert Burgess Stewart.....Winchester

CLASS III, SECTION 3

Theodore Henry Brown.....Cambridge
 Harold Walter Stoke.....Durham, N. H.

CLASS III, SECTION 4

Chester M. Alter.....West Newton
 David Frank Edwards.....Cambridge
 Huntley Nowell Spaulding.....Rochester, N. H.

CLASS IV, SECTION 1

Brand Blanshard.....New Haven, Conn.
 Stanley Smith Stevens.....Cambridge

CLASS IV, SECTION 2

Clarence Saunders Brigham.....Worcester
 Paul Herman Buck.....Cambridge
 Otto Eduard Neugebauer.....Providence, R. I.

CLASS IV, SECTION 3

George Raleigh Coffman.....Chapel Hill, N. C.
 John Huston Finley, Jr.....Cambridge

CLASS IV, SECTION 4

Edward Weeks, Jr.....Boston
 William Wilson Wurster.....Boston

FOREIGN HONORARY MEMBERS

CLASS I, SECTION 1

Bertil Lindblad.....Stockholm
 Jan Hendrik Oort.....Leiden

CLASS I, SECTION 4

Clarence Decatur Howe.....Ottawa

CLASS II, SECTION 2

Rudolf Florin.....Stockholm

CLASS III, SECTION 2

Winston Churchill.....London

CLASS IV, SECTION 1

Francisco Romero.....Buenos Aires

CLASS IV, SECTION 4

William George Constable.....Cambridge, Mass.

The following reports were then presented to the Academy:

REPORT OF THE COUNCIL

Since the last report of the Council there have been reported the deaths of twenty-six Fellows and Fellows Emeriti: Thomas Barbour, Carl Lotus Becker, Edward Wilber Berry, William Crowell Bray, Walter Bradford

Cannon, Charles Jay Connick, John Franklin Ebersole, Max Farrand, Simon Flexner, Edwin Francis Gay, Edwin Walter Kemmerer, Gilbert Newton Lewis, Leo Rich Lewis, John Livingston Lowes, Albert Matthews, John Campbell Merriam, Roger Bigelow Merriman, Thomas Hunt Morgan, William Allan Neilson, William Abbott Oldfather, William Morton Prest, Edward Kennard Rand, Theodore Leslie Shear, Carl Snyder, Harlan Fiske Stone, Jacob David Tamarkin; and two Foreign Honorary Members: Ludwig Diels, and John Maynard Keynes. Three Fellows have resigned: Frederic Adrian Delano, Wassily W. Leontief, and Edward Sagendorph Mason; and the Fellowship of Manley Ottmer Hudson has been discontinued.

Ten names have been added to the list of Fellows Emeriti: Charles Thomas Brues, George Henry Chase, William Scott Ferguson, Henry Thatcher Fowler, William Hovgaard, Edward Felix Langley, Samuel Cate Prescott, Percy Edward Raymond, La Rue Van Hook, George Benson Weston.

Thirty-three Fellows and five Foreign Honorary Members were elected by the Council and announced to Academy in May, 1945. All but William Lockhart Clayton and Howard Eugene Wilson accepted election.

Not including those elected in 1946, the roll now includes 764 Fellows and 116 Foreign Honorary Members as well as 23 Fellows Emeriti.

REPORT OF THE TREASURER

(Extract)

*RECEIPTS, 1945-1946

Academy, General:

Investment Income

\$16,295.46

Less: Income to

Special Funds 13,214.13

\$3,081.33

Assessments and Admission

Fees..... 6,208.75

\$9,290.08

Mabel S. Agassiz Fund:

Investment Income..... 116.70

Amory Prize Committee:

Investment Income..... 3,839.43

Kennelly Fund:

Investment Income..... 77.90

Life Membership Fund:

Robley D. Evans..... 200.00

Permanent Science Fund:

Boston Safe Deposit and

Trust Co., Trustee..... \$11,436.40

Investment Income..... 1,517.10

12,953.50

Publications Committee:

Investment Income..... \$2,800.80

Sale of Publications..... 513.81

3,314.61

* Excluding sales of securities.

Rumford Committee:

Investment Income	\$3,788.27	
Return of Grant	188.91	
		3,977.18

Special Expense Fund:

American Council of Learned Societies ..		1,000.00
--	--	----------

Special Alterations Fund:

Contributions		760.00
---------------------	--	--------

C. M. Warren Committee:

Investment Income	\$1,073.93	
Return of Grant	200.00	
		1,273.93

<i>Total Receipts</i>		<u>\$36,803.33</u>
-----------------------------	--	--------------------

EXPENDITURES, 1945-1946Academy, General:*

Library, Salaries..	\$2,228.00	
Books & Binding	632.38	
		\$2,860.38
General (Net)	1,416.41	
House (Net)	3,695.83	
Treasurer's Office	722.19	
Insurance	\$1,445.84	
Less Unexpired		
Premiums ...	916.18	529.66
		\$9,224.47

Mabel S. Agassiz Fund:

For Meetings		116.70
--------------------	--	--------

Amory Prize Committee

Expense		38.90
---------------	--	-------

Permanent Science Fund:

Grants	\$900.00	
Expense	103.95	
		1,003.95

President's Special Expense Account:

Expense		55.00
---------------	--	-------

Publications Committee:

General	\$1,381.62	
Lake	1,838.65	
		3,220.27

Rumford Committee:

Grant	\$250.00	
Rumford Memorial	25.25	
		275.25

<i>Special Expense Fund</i>		62.71
-----------------------------------	--	-------

<i>Special Alterations Fund</i>		3,867.22
---------------------------------------	--	----------

Warren Fund Committee:

Grants		505.00
--------------	--	--------

<i>Total Expenditures</i>		<u>\$18,369.47</u>
---------------------------------	--	--------------------

REPORT OF THE RUMFORD COMMITTEE

I have the report from the Treasurer which indicates that we have on hand a balance of \$13,832.50, and that we have an estimated income for next year of about \$3,800.

* Excluding purchases of securities.

Contribution to the present considerable balance comes from returns of earlier grants to the amount of \$730. During the past year we made but a single expenditure: \$275.25.

By general agreement we gave no Rumford medals this year on the grounds that we needed a little perspective with respect to the important wartime contributions before we next selected a man to honor.

Respectfully submitted,

HARLOW SHAPLEY, *Chairman*

May 8, 1946.

REPORT OF THE CYRUS M. WARREN COMMITTEE

The Committee had available for grants during the fiscal year 1945-1946 the sum of \$1,000 which was appropriated at the March, 1945 meeting.

The following grants were made after consideration of the applications submitted to the Committee:

To Professor Hugh J. McDonald of the Illinois Institute of Technology, a grant of \$205, for the purchase of a Beckman pH Meter to be used in connection with a study of the kinetics of dissolution of metals in various aqueous solutions.

To Professor Pierre Van Rysselberghe of the University of Oregon, a grant of \$300, to apply on the purchase of a Beckman Ultraviolet Spectrophotometer for use in the polarographic reduction of chlorophyll.

A report was received from Mr. Ralph N. Prince Textile Research Fellow, at the University of New Hampshire, in regard to a grant of \$200 awarded in 1944. In a letter dated July 17, 1945, Mr. Prince stated:

"Although considerable preliminary work was done during the year, the press of other matters was so great, that no real progress was made on the proposed project. A short report had been prepared for submission in May; however, at that time it was apparent that the work could not be continued in the near future. Therefore the matter was held up until the exact situation could be determined.

"It has developed that I shall not be located here at the Engineering Experiment Station after August 1st, and there will be little opportunity for me to continue the project in the near future.

"Therefore, I have asked that the entire amount of the grant be returned to you. I am attaching a copy of the preliminary report in addition to the check."

Respectively submitted,

FREDERICK G. KEYES, *Chairman*

May 8, 1946

REPORT OF THE COMMITTEE OF PUBLICATION

No meeting of the Publication Committee was held during the year, such business as came up having been conducted by correspondence.

The Index to Professor and Mrs. Lake's *Dated Greek Manuscripts* was published during the year.

This covers the ten fasciculi which have been published. If a supplementary fascicule should appear later, this will be separately indexed.

Professor Hatch's *Album of Dated Syriac Manuscripts* is in the press.

No new numbers of the *Proceedings* or of the *Memoirs* were published, but a manuscript by President Howard Mumford Jones has been accepted on the literature of colonial Virginia in the 17th century. It is now being composed, and will be included in the *Memoirs*.

Respectfully submitted,

ROBERT P. BLAKE, *Chairman*

May 8, 1946

REPORT OF THE LIBRARY COMMITTEE

During the year 86 bound volumes were added to the library, making a total of 47,458 now on the shelves; of this number 79 were received by gift or exchange, and seven were purchased.

In addition to the use of books in the building, 63 books and pamphlets were borrowed by 7 Fellows and 21 libraries.

The appropriation for the year ending March 31, 1946, was \$3,000, and the expenditures were as follows:

Salaries	\$2,228.00
Purchase of books and periodicals	450.43
Binding and repairing	181.95
Total	\$2,860.38

No way has been found to mitigate the conditions of congestion, under-staffing and meagre use of our library pointed out in last year's report; and, in view of the accompanying severe deterioration of the building, the council has delegated a special committee to arrange the sale of our main stock of books and periodicals. The economy resulting from cancellation of subscriptions and the assets potential in our extremely valuable holdings have meanwhile enabled the Building Committee to proceed without delay in its arduous work of rehabilitation.

Meanwhile, we have devoted our attention to the following two operations:

1. The identification and segregation of such early acquisitions as may properly be added to the archives of the Academy—chiefly the several hundred volumes of the Governor Bowdoin bequest. To these are added books associated with the Founders and other distinguished early Fellows of the Academy, making a discrete collection of about 1000 volumes, the ultimate housing of which must depend upon what can be done to give them worthy protection and care. We have had the valuable assistance of Mrs. Anne Smith in the arrangement of this collection.

2. The Librarian is by statute the custodian and distributor of the Academy's publications. These have of necessity accumulated unduly during the war, and we have been fortunate in securing the expert services of Mr. Richard Hoffman in sorting, packaging

and packing for shipment the various consignments to the many exchanging and subscribing institutions here and abroad. Your Committee have discussed at length, but tentatively, policies concerning publication and exchange that impending conditions must determine. The likelihood of a new and wide demand on our store of past *Transactions* and *Memoirs* makes early attention to these holdings imperative.

That Mr. Metcalf, Mr. Osborne and members of the Widener Library staff have shouldered the entire administrative and executive burden of checking the main collection of books, serials, and pamphlets, has alone made it possible for us to carry out the above programs.

During the exceedingly trying conditions that have necessarily attended building repairs and alterations, the Assistant Librarian has continued the Academy's business without intermission; and we cannot but deeply appreciate Mrs. Ball's persevering attention to the many and various demands of her office.

Respectfully submitted,

FREDERICK HAVEN PRATT, *Chairman*

May 8, 1946

REPORT OF THE HOUSE COMMITTEE

During the year ending March 31, 1946, the House Committee faced a number of unusual difficulties. These included the voluntary resignation of Thomas H. Gately who had held the position of janitor for twenty-six years, and the engagement of Thomas Redgate for this position. Mr. Gately was voted a monthly pension of \$50 in view of his faithful service, and he was a guest of the Council at one of its dinner meetings.

A large number of repairs were required by the recently enacted city safety regulations. Moreover certain portions of the rear wall fell without warning, fortunately without injuring anyone, and had to be replaced; and certain other unusual repairs were necessary including the cleaning and waterproofing of the elevator pit, the installation of new grates in the furnace, and repairs to the elevator. The costs of some of these are being met by special funds and do not all appear in the expenditures listed below. In addition to the necessary repairs, the Academy has improved the building by redecorating the interior and by removing the book stacks from the entrance lobby. It has also installed alternating current electric power in order to provide an emergency lighting system.

Receipts from other societies using the building were materially reduced by the fact that the building was not available for many meetings on account of the repairs being made.

As a result of the repairs and decorating, and because one of its regular meetings was replaced by a dinner meeting at the Copley Plaza Hotel, the Academy has held only two of its regular monthly meetings in its House. The other regular meetings of the Academy were held in the Mary Norton Hall of the Old South Parish House at the corner of Boylston and Dart-

mouth Streets. The other societies holding meetings at the Academy building were: the New England Botanical Club, which held eight meetings in the Reading Room; the Boston Mineral Club, one meeting.

The appropriation for House expenses for the year ending March 31, 1946, was \$2,600, and during that period \$180 was received from other societies for the use of facilities, making a total of \$2,780, which was materially exceeded as a consequence of the foregoing unforeseen expenses.

A detailed list of expenditures follows:

Janitor.....	\$1,136.13
Fuel.....	1,197.02
Electricity: Light.....	278.30
Power.....	47.85
Elevator service and repairs.....	292.09
Telephone.....	146.85
Gas.....	42.24
Water.....	53.36
Upkeep.....	353.29
Janitor's supplies and sundries.....	81.70
Thomas H. Gately's pension.....	250.00
Total.....	\$3,878.83

Respectfully submitted,
CHARLES M. SPOFFORD, *Chairman*

REPORT OF THE COMMITTEE ON THE PERMANENT SCIENCE FUND

The Committee on the Permanent Science Fund, appointed as a special committee by the Council on December 12, 1928, and yearly thereafter, has held semi-annual meetings without interruption since that date. In May, 1945, by vote of the Council the probable permanency of this committee was recognized, and it was made a Standing Committee of the Academy. For the year 1945-1946 its personnel continued in ad hoc status pending the 1946 election of officers and committees.

During the twelve months since May, 1945, the Committee has considered seventeen applications, of which five were recommended to and approved by the Council for grants-in-aid totalling \$6,425.00.

The devotion of efforts of scientists to the prosecution of the war has reduced the volume of applications for aid addressed to this Committee to one in October, 1945, a circumstance which is unique in its seventeen years of continuous experience.

Notices of the nature and availability of the Permanent Science Fund were thereupon furnished to the editors of 28 journals representing a wide coverage of natural, social and mathematical sciences, in the United States, Canada and Britain.

The Permanent Science Fund endowment was reported by its Trustee to amount to about \$315,000 in 1944. Income from this fund is paid semi-annually to the Academy, designated in the Indenture of Trust as the disbursing agent therefor. Accumulated income is

invested by our own Treasurer and its earnings added to its accumulations, which as of March 31, 1946, are of the order of \$47,000, of which the last yearly increment received from the Trustee was slightly more than \$11,000, and our earnings on our accumulations for the year were of the order of \$1,500. The precise figures are presented in the report of the Treasurer.

With the accumulations in hand and the useful size of the yearly income in sight, the Permanent Science Fund Committee is in a position to aid worthwhile projects in a significant way for the advancement through science of human welfare.

Respectfully submitted,

JOHN W. M. BUNKER, *Chairman*

May 8, 1946

On the recommendation of the Treasurer, the Academy voted that the annual assessment for the year 1946-1947 for resident Fellows be fifteen dollars.

The annual election of officers and committees resulted as follows:

Howard M. Jones.....	<i>President</i>
Roland G. D. Richardson.....	<i>Vice-President for Class I</i>
John W. M. Bunker.....	<i>Vice-President for Class II</i>
Erwin N. Griswold.....	<i>Vice-President for Class III</i>
Donald Scott.....	<i>Vice-President for Class IV</i>
Lewis Don Leet.....	<i>Corresponding Secretary</i>
Isadore Amdur.....	<i>Recording Secretary</i>
Horace S. Ford.....	<i>Treasurer</i>
Frederick H. Pratt.....	<i>Librarian</i>
Taylor Starek.....	<i>Editor</i>

COUNCILLORS FOR FOUR YEARS

Philip Franklin.....	Class I
Frederick K. Morris.....	Class II
Charles E. Wyzanski, Jr.....	Class III
John G. Beebe-Center.....	Class IV

COMMITTEE ON PERMANENT SCIENCE FUND

John W. M. Bunker, *Chairman*

Roger Adams	Albert B. Hastings
Kirk Bryan	Edward L. Moreland
Lee A. DuBridge	Payson S. Wild, Jr.

FINANCE COMMITTEE

Jerome C. Hunsaker	Henry P. Kendall
Ralph E. Freeman	Henry L. Shattuck

RUMFORD COMMITTEE

Harlow Shapley, *Chairman*

Percy W. Bridgman	Joseph H. Keenan
Harry M. Goodwin	Francis O. Schmitt
George R. Harrison	Edwin H. Land

C. M. WARREN COMMITTEE

Frederick G. Keyes, *Chairman*

Louis F. Fieser	Avery A. Morton
Charles A. Kraus	Walter C. Schumb
Grinnell Jones	Kenneth L. Mark

COMMITTEE OF PUBLICATION

Taylor Starck, *Chairman, ex officio*

Ernest H. Huntress	Class I
Kenneth V. Thimann	Class II
Thomas North Whitehead	Class III
Kenneth J. Conant	Class IV

COMMITTEE OF THE LIBRARY

Frederick H. Pratt, *Chairman ex officio*

Raymond C. Archibald	Class I
Charles A. Weatherby	Class II
Francis N. Balch	Class III
Henry B. Washburn	Class IV

AUDITING COMMITTEE

Donald S. Tucker Thomas H. Sanders

HOUSE COMMITTEE

Charles M. Spofford, *Chairman*H. Addington Bruce Robert P. Bigelow
John B. Wilbur

COMMITTEE ON MEETINGS

The President

The Recording Secretary

Edgar S. Brightman Cecilia Payne-Gaposchkin
Crane Brinton Seymour E. Harris

The general subject of the communication was *The Ecological Approach to Land Use*, treated by three speakers, as follows:

Edward H. Graham: *The Ecologists' Viewpoint*.Seymour E. Harris: *The Economists' Viewpoint*.Edward A. Ackerman: *The Geographers' Viewpoint*.

The meeting was dissolved at 10:30 P. M.

One Thousand Three Hundred and Twelfth Meeting

OCTOBER 9, 1946.—STATED MEETING

The Academy met at its House at 8:20 P. M.

The President in the Chair.

There were present sixty Fellows and fourteen guests.

The records of the meeting of May 8 were read and approved.

A vote was taken on a proposed amendment to the Statutes, Chapter XI, Article 2, which had been recommended to the Academy by the Council at the annual meeting last May. The amendment called for the addition of the Committee on the Amory Prize to the Standing Committees of the Academy by insertion in Chapter XI, Article 2, of the Statutes, of the following:

The Committee on the Amory Prize, to consist of seven Fellows, who shall consider all persons eligible for this

award and recommend to the President and Fellows of the Academy a suitable recipient of the award according to the terms of the gift.

The amendment was adopted unanimously.

The Rev. M. J. Ahern, S. J., representative of the Academy at the observance of the one-hundredth anniversary of the Fine Arts Section of the Royal Belgian Academy of Sciences and Letters in Brussels, July 24-27, reported to the Fellows and guests. He presented to the President, for the Academy, a medal from the Belgian Academy.

The Corresponding Secretary reported the receipt of letters accepting Fellowship from the following: Chester M. Alter, James Gilbert Baker, John Landes Barnes, Paul Doughty Bartlett, George Wells Beadle, Roland Frank Beers, Brand Blanshard, Clarence Saunders Brigham, Theodore Henry Brown, Harvey Hollister Bundy, Subrahmanyam Chandrasekhar, Ralph Erskine Cleland, George Raleigh Coffman, John Sloan Dickey, Lee Alvin Du Bridge, David Frank Edwards, Howard Wilson Emmons, John Franklin Enders, Cornelius Searle Hurlbut, Jr., Charles Alderson Janeway, Otto Eduard Neugebauer, James Lee Peters, Kenneth David Roeder, Huntley Nowell Spaulding, Stanley Smith Stevens, Robert Burgess Stewart, Walter Hugo Stockmayer, Harold Walter Stoke, Julius Adams Stratton, Siegfried Josef Thannhauser, Edward Augustus Weeks, Jr., William Wilson Wurster; and of letters accepting Foreign Honorary Membership from Winston Churchill, William George Constable, Rudolf Florin, Clarence Decatur Howe, Bertil Lindblad, Jan Hendrik Oort, and Francisco Romero; also letters declining Fellowship from Paul Herman Buck and John Huston Finley, Jr.

The President announced that at the November meeting, the Academy would go into a Committee of the Whole to consider the Report of the Commission on the Present Status and Future of the Academy.

He also made preliminary announcements concerning the February conference on The Artist in American Society.

New members were introduced by sponsoring Fellows.

The following communication was presented:

William A. Jackson: *Forgeries and Facsimiles*.

One paper was presented by title: *Lower Permian Insects from Oklahoma. Part 1*, by F. M. Carpenter.

The meeting was dissolved at 9:45 P. M.

One Thousand Three Hundred and Thirteenth Meeting

NOVEMBER 13, 1946.—STATED MEETING

The Academy met at its House at 8:25 P. M.

The President in the Chair

There were present sixty-six Fellows and one guest.

The records of the meeting of October 9 were read and approved.

The President announced the inaugural lecture of The Arthur Dehon Little Memorial Lecture-ship series to be given by Sir Edward V. Appleton at the Massachusetts Institute of Technology, November 19, 1946. Members of the Academy were invited to attend.

New members were introduced by sponsoring Fellows.

It was moved that the Fellows present constitute a Committee of the Whole to consider the Report of the Commission on the Present Status and Future of the Academy. The motion was carried.

The President appointed Dean George R. Harrison chairman of the Committee of the Whole. The Recording Secretary acted as secretary of the Committee. It was pointed out by the chairman that action by the Committee of the Whole would take the form of favorable or adverse recommendation to the Council and Academy.

Kirtley F. Mather, chairman of the Commission, summarized the report and listed the following priorities which had been assigned by the Commission to its recommendations:

First—Increase in Membership (pp. 19–21 of Report)

Second—Establishment of a Committee on Nominations (pp. 21–22 of Report)

Third—The focus of attention upon the regional responsibilities of the Academy (pp. 17–19 of Report)

Fourth—Creation of the position of Executive Officer (pp. 37–38 of Report)

Fifth—Changes in publication policy (pp. 31–35 of Report)

Sixth—Acceptance of responsibility for leadership in formation of public opinion on matters of import to the body politic (pp. 14–16 of Report)

Seventh—Creation of a committee for the award of prizes or medals to outstanding younger American scholars (pp. 40–41 of Report).

The following recommendations were mentioned for future discussion without assignment of priorities:

Changes in the character of meetings of the Academy (pp. 22–28 of Report).

Additional changes in the House of the Academy (pp. 28–29 of Report).

Greater use of the Academy's House by outside organizations (pp. 30–31 of Report).

Sale of portions of the Library (pp. 35–36 of Report). (The majority of recommendations concerning the Library have already been realized as of this date.)

Support of expanded program by additional income resulting from the sale of the Library and by dues from the increased number of Fellows (pp. 38–39 of Report).

The following actions were taken by the Committee of the Whole:

1. It was moved that the Committee report favorably on the recommendation that "the number of Fellows shall not exceed 1000, of whom not more than 700 shall be residents of Massachusetts, nor shall there be more than 275 in any one Class."

In the discussion it was pointed out that the reduction of the percentage of Fellows from Massachusetts from 75 per cent to 70 per cent was intended to broaden the base of the membership, and that the primary purpose of the recommendation was to add vitalizing Fellows to the Academy membership and not to obtain additional revenue.

The motion was carried.

2. It was moved that the Committee report favorably on the recommendation calling for "the establishment of a Standing Committee on Nomination of Fellows and Foreign Honorary Members, consisting of two Fellows from each Class, not members of the Council, to be elected at the Annual Meeting for terms of two years, with the elections so arranged that one member of the Committee will be elected each year from each Class, and with the President of the Academy serving ex officio as the Chairman of the Committee."

It was moved that the original motion be amended to favor a Committee consisting of four Fellows from each Class, chosen one each from the four Sections, and that this representation be preserved when filling vacancies in the Committee. The motion to amend was lost.

In the discussion it was pointed out that the creation of a standing Committee on Nomination of Fellows and Foreign Honorary Members is not intended to replace but to supplement existing nomination procedures.

The original motion was carried.

3. It was moved that the Committee report favorably on the recommendation that the Fellows "focus atten-

tion upon the regional responsibilities of the Academy, but do not be unmindful of its national interests."

The motion was carried.

In the discussion of a suggestion for a regional study of New England, it was pointed out that outside financial support and qualified administrative personnel would be required for surveys as outlined in the Report of the Commission. It was also pointed out that since the living problems of New England have social and political implications and are therefore certain to become controversial at times, the Academy should be prepared to become involved in such controversies if it acts favorably on this suggestion of the Commission.

4. It was moved that the Committee report favorably on the recommendation calling for "the establishment of the position of Executive Officer of the Academy" whose duties are described in the Report of the Commission.

In the discussion, the type of person required for this position was described. It was pointed out that the Treasurer was of the opinion that funds would be available, chiefly as the result of the sale of the Library, to pay a salary sufficient to attract an Executive Officer of the proper qualifications.

The motion was carried.

The Committee of the Whole rose to report at 10:30 P. M. and then dissolved.

The meeting was dissolved at 10:35 P. M.

One Thousand Three Hundred and Fourteenth Meeting

DECEMBER 11, 1946.—STATED MEETING

The Academy met at its House at 8:17 P. M.

The President in the Chair.

There were present forty-nine Fellows and six guests.

The records of the meeting of November 13 were read and approved.

The President announced the appointment of John W. M. Bunker as Corresponding Secretary to succeed L. Don Leet, whose new duties outside the state have necessitated his resignation as Corresponding Secretary. Dean Bunker will serve until the next duly elected incumbent takes office.

The Corresponding Secretary reported on the actions taken by the Council at its meeting of this date.

New members were introduced by sponsoring Fellows.

The President announced that the speaker for the January meeting would be Professor Brand Blanshard of Yale University, who would speak

on certain aspects of man's ability to comprehend the rapidly increasing store of human knowledge.

The President informed the members that four panel discussions had been planned for the February National Conference on the Support of the Visual Arts and that admission would be by ticket. He stated that the members would be informed shortly of the complete program for the conference, and of the method of applying for admission tickets.

The following communication was presented:

Julius A. Stratton: *Electronics in War and Peace*.

The meeting was dissolved at 9:55 P. M.

One Thousand Three Hundred and Fifteenth Meeting

JANUARY 8, 1947.—STATED MEETING

The Academy met at its House at 8:25 P. M.

The President in the Chair.

This meeting had been designated as Ladies' Night, and there were present about one hundred and twenty-five Fellows and guests.

The records of the meeting of December 11, 1946 were read and approved.

The Corresponding Secretary, on behalf of the Special Committee on Statutory and Legislative Changes, presented a motion recommending that the Academy rescind the current Standing Votes 1-4 inclusive, since they are no longer operative. The motion was carried unanimously.

A new member was introduced by a sponsoring Fellow.

The President outlined the final program for the February National Conference on the Support of the Visual Arts and reminded members to apply for tickets to the scheduled panel discussions.

The following communication was presented:

Brand Blanshard: *Can Man Expand with Expanding Knowledge*.

The meeting was dissolved at 9:40 P. M.

One Thousand Three Hundred and Sixteenth Meeting

FEBRUARY 14 and 15, 1947.—STATED MEETING

The Academy met at its House.

The President opened the meeting.

The meeting had been designated as the "Conference on the Artist in Contemporary American Society" and there were present about

one hundred and seventy Fellows and invited guests. The Conference was divided into four panel discussions, each with six scheduled speakers, as follows:

February 14:

10:00 A. M.—12:30 P. M. Panel Discussion I: *What does the buyer want from the artist?* Chairman, Charles S. Sawyer, Worcester Art Museum.

2:30—5:00 P. M. Panel Discussion II: *Can the artist supply what is wanted?* Chairman, Edward A. Weeks, The Atlantic Monthly.

February 15:

10:00 A. M.—12:30 P. M. Panel Discussion III: *The problem of marketing agencies.* Chairman, Bartlett H. Hayes, Jr., Addison Gallery.

2:00 P. M.—4:30 P. M. Panel Discussion IV: *The artist and the community: the problem of interaction.* Chairman, Howard Mumford Jones.

At 8:30 P. M. on February 14, W. G. Constable, Boston Museum of Fine Arts, delivered a public lecture entitled, *Art and Everyday Life*.

In conjunction with the Conference, an exhibition was arranged on the first floor of the Academy, to illustrate the way in which typical problems within various industries are handled by the contemporary industrial designer. The exhibition was organized by the Institute of Modern Art, Boston, and was open to the public Monday through Friday afternoons for four weeks beginning February 17.

One Thousand Three Hundred and Seventeenth Meeting

MARCH 12, 1947.—STATED MEETING

The Academy met at the Colonial Room of the Copley Plaza Hotel at 7:15 P. M.

The President in the Chair.

This meeting had been designated as the Second Annual Dinner meeting and there were present seventy-seven Fellows, seven of whom were honored guests, and five non-member honored guests.

The President introduced the honored guests.

He announced appointment of the Nominating Committee as follows:

Philip Franklin, of Class I, *chairman*

Louis C. Graton, of Class II

Abbott P. Usher, of Class III

Paul J. Sachs, of Class IV.

The Corresponding Secretary presented recommendations voted by the Council at a special

meeting on March 11. The recommendations were in response to a report by the Treasurer and provided for:

1. Use of funds to the amount of \$1,291, from the sale of the Library, to offset the deficit in over-all operations for the fiscal year 1946-1947.

2. Specified appropriations for the fiscal year 1947-1948 as follows:

for House expenses:

Operating.....	\$ 5,600
Meetings.....	2,500
Stenographer.....	2,100

for Library expenses:

Salaries.....	3,000
Other.....	500

for Treasurer's expense..... 1,500

for President's expense..... 600

Amory Fund..... 500

Thomas Barbour Fund..... 250

Kennelly Fund..... 75

Permanent Science Fund..... 2,000

Publication Committee Fund..... 1,000

Rumford Fund..... 4,000

Warren Fund..... 1,000

Total..... \$24,625

The recommendations were approved as presented.

The Corresponding Secretary moved that the Academy approve a bill for presentation to the present session of the General Court to amend the Academy Charter. The bill would enable the Academy to determine the size of its membership and to pass regulations concerning election, discipline and expulsion of members. The motion was carried.

The Corresponding Secretary informed the members of the action of the Council to favor operation on yearly appropriations, without carry over of unexpended balances. This policy calls for advance appropriations for foreseeable expenses to the Standing Committees, which may apply to the Council for additional appropriations. He also stated that all occupants of the House of the Academy will share in the operating expense.

The Recording Secretary announced that a symposium on the Science Talent Search was planned for the April meeting.

The President reviewed recent Academy activities and urged greater participation by the

members in the affairs of the Academy. He announced the receipt of a gift of \$5,000 to be known as the Barbour Fund, the income of which is available for general purposes.

The following communications were presented:

I. A. Richards: *The Language of the Specialist*.

William H. Davis: *The Art and Science of Labor Relations*.

The meeting dissolved at 10:40 P. M.

One Thousand Three Hundred and Eighteenth Meeting

APRIL 9, 1947.—STATED MEETING

The Academy met at its House at 8:20 P. M.

The President in the Chair.

There were present twenty-five Fellows and twenty-eight guests.

The records of the meetings of January 8, February 14 and 15, and March 12 were read and approved.

The Recording Secretary reported on the Initiating Meeting of the Inter-Society Committee on Science Foundation Legislation held in Washington on February 23. He also gave the results of a poll dated March 13, of delegates to the Inter-Society Committee, on questions of composition, policies, and program of a National Science Foundation.

Bart J. Bok, representative of the Academy at the first National Conference on UNESCO held in Philadelphia on March 24-26, reported on the results of the conference.

The Corresponding Secretary announced that the Council had started consideration of the recommendations of the Committee on Revision of the Statutes at its April meeting and planned to complete the discussion at its May meeting. He announced that the report to the Fellows would be made at the October meeting.

The general subject of the communication was the *National Science Talent Search*. The speakers were Harlow Shapley, Watson Davis, and Fletcher G. Watson.

At the conclusion of the discussion of the communication, it was moved and seconded that: "It is the sense of this meeting that the American Academy of Arts and Sciences should concern itself with the discovery, encouragement, and development of latent scientific talent in New England and especially in Massachusetts. It is

therefore recommended that a Committee be formed under the auspices of the American Academy of Arts and Sciences, which will be broadly representative of all groups interested in science education at the secondary school level, and that this Committee be instructed to explore ways for encouraging our potential young scientists."

The motion was carried.

The meeting dissolved at 10:25 P. M.

One Thousand Three Hundred and Nineteenth Meeting

MAY 14, 1947.—ANNUAL MEETING

The Academy met at its House at 8:30 P. M.

The President in the Chair.

There were present forty-three Fellows and seven guests.

The records of the meeting of April 9 were read and approved.

The Corresponding Secretary read the names of the newly elected members of the Academy, as follows:

FELLOWS

CLASS I, SECTION 1

Howard Hathaway Aiken..... Newton

CLASS I, SECTION 2

Hans Albrecht Bethe..... Ithaca, N. Y.
Edward Uhler Condon..... Washington, D. C.

CLASS I, SECTION 3

Paul Clifford Cross..... Providence, R. I.
Clark Conkling Stephenson..... Cambridge

CLASS I, SECTION 4

Charles Winters MacGregor..... Belmont

CLASS II, SECTION 3

Arnold Gesell..... New Haven, Conn.

CLASS II, SECTION 4

Arthur Wilburn Allen..... Brookline
David Lawrence Belding..... Boston
Sanford Burton Hooker..... West Roxbury
Francis Minot Rackemann..... Boston
James Stevens Simmons..... Brookline
Richard Mason Smith..... Boston
Merrill Clary Sosman..... Chestnut Hill
Shields Warren..... West Newton

CLASS III, SECTION 1

Mark DeWolf Howe..... Cambridge
John Lord O'Brian..... Washington, D. C.

CLASS III, SECTION 2

William Phillips..... North Beverly
Sumner Welles..... Oxon Hill, Md.

CLASS III, SECTION 3

George Pierce Baker.....Boston
Fritz Jules Roethlisberger.....Cambridge

CLASS III, SECTION 4

Thomas Dudley Cabot.....Weston
William Henry Claflin, Jr.....Belmont
Mildred McAfee Horton.....Wellesley
Ralph Lowell.....Westwood

CLASS IV, SECTION 1

Norman Burdett Nash.....Boston

CLASS IV, SECTION 2

Ruth Fulton Benedict.....New York, N. Y.
Wilbur Kitchener Jordan.....Cambridge

CLASS IV, SECTION 3

Ivor Armstrong Richards.....Cambridge
William Freeman Twaddell.....Providence, R. I.

CLASS IV, SECTION 4

Richard Burgin.....Brookline
John Dos Passos.....Provincetown
Milton Edward Lord.....Boxford
Lewis Mumford.....Amenia, N. Y.

FOREIGN HONORARY MEMBERS

CLASS I, SECTION 1

Edward Arthur Milne.....Oxford
Meghnad Saha.....Calcutta
G. A. Shajn.....Simeis, U. S. S. R.
Ivan Matveitch Vinogradoff.....Moscow

CLASS I, SECTION 2

Sir George Paget Thomson.....London

CLASS II, SECTION 1

Wen-hao Wong.....Nanking

CLASS II, SECTION 2

P. Maheshwari.....Dacca, India
Alf Erling Forsild.....Ottawa

CLASS II, SECTION 3

Augustus Daniel Imms, Tipton St. John's, Devonshire

CLASS III, SECTION 1

Paal Berg.....Oslo

CLASS IV, SECTION 1

Godfrey Hilton Thomson.....Edinburgh

CLASS IV, SECTION 3

Hamilton Alexander Rosskeen Gibb.....Oxford
Joseph Klausner.....Jerusalem

The following annual reports were read and approved:

REPORT FROM THE COUNCIL

Since the last report of the Council, there have been reported the deaths of twenty-three Fellows: Wilfred Bolster, Willa Sibert Cather, Henry Helm Clayton,

Irving Fisher, Allyn Bailey Forbes, Roger Sherman Greene, Hammond Vinton Hayes, William Clifford Heilman, Edward Godfrey Huber, Carl Newell Jackson, Herbert Spencer Jennings, Willis Linn Jepson, Kirsopp Lake, Henry Lefavour, Edward Laurens Mark, Albert Davis Mead, John Anthony Miller, Curtis Hidden Page, Leo S. Rowe, William Berryman Scott, Horatio Elwin Smith, Bentley Wirt Warren, Westel Woodbury Willoughby; and of five Foreign Honorary Members: Miguel Asin y Palacios, Sir Joseph Barcroft, William Warwick Buckland, Pierre Janet, and Friedrich Paschen. Four Fellows have resigned: Howard Sylvester Ellis, Gottfried Haberler, Perry Gilbert Eddy Miller, and Harold Glenn Moulton.

Six Fellows have been classed as Emeriti: Reginald Aldworth Daly, Joseph Horace Faull, Sidney Bradshaw Fay, James Geddes, Jr., Charles Howard McIlwain, and George Edmond Russell.

One transfer has been made from Foreign Honorary Member to Fellow: William George Constable.

In May 1946, the election by the Council of thirty-five Fellows and seven Foreign Honorary Members was announced to the Academy: all except three of these accepted election.

The roll now includes 764 Fellows, 29 Fellows Emeriti and 116 Foreign Honorary Members (exclusive of those elected in 1947).

The Academy is informed that its petition introduced into the House and the Senate of Massachusetts to amend the Act which governs the number of members of the Academy will be given a hearing on May 19, 1947, at which officers of the Academy will be present.

The Council has voted that consideration of proposed amendments to the Statutes of the Academy will be the principal order of business of the stated meeting of the academy in October, 1947.

REPORT OF THE TREASURER

(Extract)

*RECEIPTS, 1946-1947.

Academy, General:

Investment Income

\$18,673.06

Less: Income to

Special Funds 13,776.36

\$4,896.70

Assessments and Admission

Fees.....6,460.00

\$11,356.70

Mabel S. Agassiz Fund:

Investment Income.....108.40

Amory Prize Committee:

Investment Income.....3,956.60

Thomas Barbour, Bequest from Estate of....5,000.00

Carnegie Corporation, for Visual Arts Conference.....2,000.00

* Excluding sales of securities.

<i>Kennelly Fund:</i>		
Investment Income.....	\$75.88	
<i>Life Membership Fund:</i>		
From Eric G. Ball.....	200.00	
<i>Permanent Science Fund:</i>		
Boston Safe Deposit and Trust Co., Trustee.....	\$11,333.74	
Investment Income.....	1,788.60	
		13,122.34
<i>Publications Committee:</i>		
Investment Income.....	\$2,710.00	
Sale of Publications.....	696.61	
Lake Publications.....	276.05	
		3,682.66
<i>Rumford Committee:</i>		
Investment Income.....	\$4,139.60	
Return of Grant.....	30.74	
		4,170.34
<i>Library Sale Fund:</i>		
From Linda Hall Library Trustees.....	140,000.00	
<i>Special House Alterations Fund:</i>		
Contributions and Sales.....	168.50	
<i>C. M. Warren Committee:</i>		
Investment Income.....	997.28	
Total Receipts.....	\$184,838.70	

*EXPENDITURES, 1946-1947

<i>Academy, General:</i>		
Library, Salaries..	\$2,492.00	
Books & Binding..	413.14	
		\$2,905.14
General (Net).....	2,773.91	
House (Net).....	5,014.33	
President's Expense.....	224.93	
Treasurer's Expense (Net)...	851.92	
Insurance.....	\$1,157.63	
Less Unexpired Premiums...	635.20	522.43
		\$12,292.66
<i>Mabel S. Agassiz Fund:</i>		
For Meetings.....	108.40	
<i>Amory Prize Committee</i>		
Expense.....	76.50	
<i>Carnegie Corporation, for Visual Arts Conference</i>		
.....	2,131.82	
<i>Permanent Science Fund:</i>		
Grants.....	\$8,625.00	
Expense.....	9.50	
		8,634.50
<i>Publications Committee:</i>		
General.....	\$821.04	
Lake.....	12.56	
Hatch.....	2,690.19	
		3,523.79
<i>Rumford Committee:</i>		
Grants.....	800.00	

* Excluding purchases of securities.

<i>Library Sale Fund:</i>	
Boxes and Express.....	\$2,109.67
<i>Special Expense Fund (Mather Committee)...</i>	327.37
<i>Special House Alterations Fund.....</i>	15,378.55
<i>C. M. Warren Committee:</i>	
Grants.....	1,000.00
Total Expenditures.....	\$46,383.26

REPORT OF THE RUMFORD COMMITTEE

Three research grants have been made:

To Dr. Leo L. Baranek, Cruft Laboratory, Harvard University, to assist in researches on the transfer of acoustic energy into heat energy in samples of fibrous materials, such as cotton, kapok, and Fiberglas. \$400.

To Dr. O. Oldenberg, Physics Laboratory, Harvard University, to assist in the investigation of the kinetics of free hydroxyl radicals, \$400.

To Dr. Willem J. Luyten of the University of Minnesota, to assist in researches on the motions and luminosities of dwarf binary stars, \$250.

One application is pending. Unused remainders of grants have been returned from F. Schlesinger, C. T. Elvey, D. K. Fromm, and G. Z. Dimitroff, in the total amount of \$764.98.

The balance in the Rumford Fund available on this date for the use of the Committee is nearly seventeen thousand dollars, and the Treasurer estimates the income for 1947-1948 will be \$4,120.

The Committee plans to consider the advisability of making larger grants in aid of research than has heretofore been the custom. For several years we have limited our grants to four hundred dollars and less.

The Committee is in the process of selecting a candidate for the Rumford Medals, to be awarded at some meeting of the Academy during the year 1947-1948.

Satisfactory reports have been received from some Rumford Fund grantees. The Committee is in the embarrassed possession of a valuable diamond which has been returned by a grantee whose researches no longer require this accessory. The Council may wish to decide what officer or agency should be designated keeper of the Academy's jewels.

Respectfully submitted,

HARLOW SHAPLEY, *Chairman*

May 14, 1947

REPORT OF THE CYRUS M. WARREN COMMITTEE

The Committee had available for grants during the fiscal year 1946-1947 the sum of \$1,000.00, which was appropriated at the March, 1946 meeting.

The following grants were made after consideration by the Committee of the applications submitted:

To Professor I. Amdur of the Massachusetts Institute of Technology, a grant of \$300 for the purchase of

pure deuterium gas to be used in extending his research on scattering of high velocity hydrogen atoms by hydrogen molecules to systems involving all possible combinations of atoms and molecules of deuterium as well as atoms and molecules of hydrogen.

To Professor Edward R. Atkinson, University of New Hampshire, a grant of \$400 to be used toward the purchase of a Heyrovsky Polarograph for use in connection with research on the action of reducing agents on diazotized amines.

To Professor Pierre Van Rysselberghe, University of Oregon, a grant of \$300 to be applied on the purchase of an electric analyzer and two sets of platinum electrodes, items needed for continuation of research in the field of solutions.

A letter was received from Professor E. C. Gilbert of Oregon State College reporting on a 1940 grant from the Cyrus M. Warren Fund. The thermometer bridge purchased by the aid of a grant is functioning but there has been delay in publication of the material. Reprints will be forthcoming shortly.

A report from Professor Atkinson states that the polarograph has been in daily use and that a paper based on work with the instrument will be presented at the American Chemical Society meeting in New York in September.

Professor Amdur reports that the pure deuterium gas has been obtained and the research is still in progress. It is expected that experimental results will be available during the coming year.

Reprints have been received as follows:

Studies on Film-Forming Yeasts. Acid Production by Zygoichia and Zygochansula by Walter J. Nickerson. *Mycologia*, 36, 224-233 (1944).

On the Metabolism of Zygosaccharomyces by Walter J. Nickerson and William R. Carroll. *Archives of Biochemistry*, 7, 257-271 (1945).

Respectfully submitted,

FREDERICK G. KEYES, *Chairman*

May 14, 1947

REPORT OF THE COMMITTEE OF PUBLICATION

The Committee has held only one meeting during the year, this a fairly long one; but a considerable amount of work was done by correspondence, since it seemed difficult to get all the members together more frequently. As only a few papers were submitted for publication, regular meetings were hardly needed.

The most considerable publication issued was the *Album of Dated Syriac Manuscripts* by W. H. P. Hatch. All the editorial work in this volume was done by the previous Editor of Publications. The volume was ready except for title page, binding, and cover jacket, and the final arrangements with the Harvard University Press. The Harvard University Press according to an earlier contract undertakes the marketing of the book and distributes review copies. The binding was delayed for a number of months because of shortage

of materials, but the volume finally appeared early in 1947. Review copies have been distributed.

Late in 1946 Howard M. Jones, *The Literature of Virginia in the Seventeenth Century* appeared as Memoirs, Volume XIX, Part 2. This had been accepted in the year 1945-1946 and was partially in type when the incumbent editor assumed office.

One number of the Proceedings, Volume 76, No. 2, was accepted and published, a continuation of Frank M. Carpenter's study of *Permian Insects from Oklahoma*.

As a special publication the Committee accepted the account of the panel discussion on the *Ecological Approach to Land Use* held at the Academy's meeting of May 8, 1946. This had been printed in the *Journal of Soil and Water Conservation*, Volume I, No. 2 (October, 1946). Offprints were made and provided with a special cover and made available to Fellows.

Furthermore, the editor carried out the policy inaugurated last year of having planographed and distributed abstracts of the communications to the Academy. In this series was included a summary of the Report of the Conference on the Support of the Visual Arts held at the Academy's House on February 14 and 15, 1947.

No action is pending on any manuscript and nothing is in press. Pending are negotiations for the possible publication of a *Study of Massachusetts Facilities for Child Health* carried through by the American Pediatric Association. A meeting has been arranged for May 14 which will perhaps result in a proposal to be laid before the Editorial Committee.

The Publication Accounts were submitted by the Treasurer as of March 12, 1947. They show an overdraft of \$2,182.90 in the Hatch Account but a credit balance of \$9,902.79 in the General Account and a credit balance of \$1,590.81 in the Lake Account. By Council action on March 11, 1947, these accounts have all been consolidated and \$1000 appropriated for the initial publication expenditures for 1947-1948. The funds in sight are therefore ample for normal publication activities.

Respectfully submitted

TAYLOR STARCK, *Chairman*

May 14, 1947

REPORT OF THE LIBRARY COMMITTEE

We submit the following statement of account:

Appropriated

Salaries.....	\$2,700.00
Books, Periodicals, Binding.....	600.00
	\$3,300.00

Expended

Salaries.....	\$2,492.00
Binding.....	164.90
Repair.....	111.00
Books of reference.....	137.24
	\$2,905.14

Funds appropriated to the library have long covered several fields: first, the care and circulation of books, serials and pamphlets, represented in the salary of the Assistant Librarian; secondly, the filling and dispatch of completed publications and the reception of items exchanged or subscribed for, including their binding, again implemented by the same salary; third, the operation of the Academy's central office, subject to the needs of its officers, such as handling current announcements, roll of membership, collection of dues, telephone service, and items arising in connection with meetings and outside organizations—these also devolving upon the versatility of the Assistant Librarian. And it should not be forgotten that for many years that office has had, in the oversight of nearly 50,000 volumes, the sole assistance of the resident custodian of the building, separately supported by the building appropriation—these together constituting the library staff.

Economies effected by present changes are important, though as yet few. Periodical subscriptions have been virtually eliminated. From now on there will be bills for essential reference works, but none for binding other than of our own publications. Repair work on books, for years at a standstill, no longer threatens the treasury. But against these economies the library must for the time being shoulder one increase in expenditure—that of extra employment. During the concurrent renovation of the building and dismantling of stacks, the office has been sorely taxed to meet the world-wide renewal of demand for our publications, so long dammed up by war. The work of checking, sorting and shipping this material is arduous and requires specific skilled attention. This demand has fortunately been met by Mr. Richard Hoffman's experienced service; and such abilities will be required as long as the present organization of our exchange program continues.

A collection of about 850 volumes, the gift of founders and other early donors, awaits distribution to special libraries or appropriate depositories, with the desirability in mind of retaining certain items of special historical significance, some of which have been restored with great skill by Miss Irene Tilden. The majority of the volumes, the bequest of Governor Bowdoin, is fittingly destined for deposit in the James Bowdoin collection at Bowdoin College. We are grateful to Mrs. Anne Smith, who has always stood ready to serve in emergencies (as during Mrs. Ball's recent unfortunate wrist injury) for her interest and efficient aid in listing and arranging all of these ancient treasures.

Respectfully submitted,

FREDERICK HAVEN PRATT, *Chairman*

May 14, 1947

REPORT OF THE HOUSE COMMITTEE

At the request of the Lowell Institute Cooperative Broadcasting Council, office space of 1200 square feet has been provided on the fourth floor of the Academy House by removing the bookcases and books formerly occupying the westerly portion of this floor; the walls

have been redecorated, the floor refinished and fluorescent lighting fixtures installed, making the quarters for the Council highly satisfactory. One-half of the cost of the repairs is to be paid by the Institute which also pays a reasonable amount towards maintenance. Prior to the allotment of this space the Council staff used the Reception Room on the Ground Floor.

The packing of books for shipment to the Linda Hall Library in Kansas City, as per contract, has been nearly completed. Due to the lack of storage space in Kansas City, the Academy has temporarily stored a considerable number of packed books in boxes.

During the year of 1946-1947 meetings have been held in the Academy Building as follows:

Antiques Committee, Massachusetts Federation of Women's Clubs	3
Boston Mineral Club	9
Brookline Bird Club	1
Children's Museum, Trustees	4
Greater Boston Orchestral Society	1
Institute for Religious and Social Studies	10
New England Botanical Club	8
N. E. Farm and Garden Association	9
Students' Branch, American Management Assoc.	1
Women's Travel Club	1
Total	47

There was received from these Societies and from the Lowell Institute Cooperative Broadcasting Council and the Boston Society of Natural History for use of facilities, the sum of \$593.16. The total expenditures, however, for operation were as follows:

Custodian	\$1,693.80
Fuel	1,234.17
Electricity (Light and Power) ..	432.80
Elevator (Service and Repairs) ..	222.38
Telephone	245.42
Gas	17.32
Water	51.40
Equipment	600.36
Upkeep	291.41
Janitor's supplies and sundries ..	218.43
Thomas H. Gately's pension	600.00
	\$5,607.49
Receipts	593.16

Total Net Expenses

\$5,014.33

The appropriations for the House Committee for the year 1945-1946 were:

Operation	\$3,600.00
Additional salary to T. L.	
Redgate	450.00
	\$4,050.00

The House Committee recommends the adoption of revised Rules for the Use of the House as follows:

Preamble to be revised and simplified.

Section 4—Rule is modified by changing the rates charged for the use of the rooms as follows: For the use of the Assembly Room the rate is raised from \$10 to \$15. For the use of the Reading Room the rate is changed from \$15 to \$10, if no refreshments are served. If refreshments are served, \$5 additional will be charged. Strike out in the second line "and the Reception Room" and also in the last line "for small groups" and insert "in special cases."

Section 5—The rules for keeping a visitors' book is stricken out as this rule has not been observed in the past.

Section 6—Substitute "House Committee" for "Assistant Librarian."

Section 7—Revise by striking out in the second line the words "introduced by fellows" and in the third line "and endorsed by the Council. Societies;" also strike out "not on the approved list should make" and in the same line "to the Assistant" and on the fifth line strike out "Librarian" and insert "House Committee should be made." Strike out the last two words "and in" and also, strike out the last line.

The rules will then read as follows:

RULES FOR THE USE OF THE HOUSE

Preamble

The Council wishes to encourage the use of the Academy House for meetings of learned and cultural societies in accordance with the following rules:

Rules

1. The House of the Academy shall be available for the use of Fellows of the Academy at all reasonable hours.
2. Except as otherwise provided, the privilege of using the House of the Academy shall be enjoyed by Fellows only, who shall, however, be permitted to bring guests with them to a number not exceeding twenty.
3. Fellows introducing guests shall be responsible for any injury caused by them to the property of the Academy.
4. Fellows or organizations introduced by them may use the Committee Room on the ground floor and also the Assembly Hall and the Reading Room. For the use of the rooms on the ground floor no charges will be made. For the use of the Assembly Hall a charge of \$15 will be made for each occasion; for the Reading Room there will be a charge of \$10 if no refreshments are served; or \$15, if there are refreshments. An additional charge of \$5 will be made for each hour or fraction of an hour during which the rooms are occupied after 11 P. M. The House Committee is authorized, however, to reduce the charges in special cases.
5. Fellows, or organizations introduced by them, desiring to use either of the two large rooms for a meeting shall make application to the House Committee not less than one week in advance of the time at which the meeting is to be held.
6. The privileges of the House shall be limited to Fellows and their guests and to learned and cultural societies, approved by the House Committee. Written application to the House Committee should be made at least two weeks in advance of the proposed meeting.

Respectfully submitted,

CHARLES M. SPOFFORD, *Chairman*

May 14, 1947

REPORT OF THE COMMITTEE ON THE PERMANENT SCIENCE FUND

The Committee on the Permanent Science Fund recommended the following grants-in-aid which were approved by the Council of the American Academy of Arts and Sciences for the year 1946-1947.

October 1946

1. To C. L. Hayward, Associate Professor of Zoology, Brigham Young University, Provo, Utah; for travel and publication expense in an investigation of the Ecology of Alpine Biotic Communities in western North America, \$500.
2. To Seymour E. Harris, Professor of Economics, Graduate School of Public Administration, Harvard College; for clerical assistance in extending a study of the Economic Aspects of the Release of Atomic Energy, \$600.
3. To Herbert L. Eastlick, Associate Professor of Zoology, State College of Washington, Pullman, Washington; for equipment, expendable materials, and publication of a study on the Embryology of Melanoblasts in the Silkie Fowl, \$350.
4. To C. C. Hoff, Assistant Professor of Zoology and Parasitology, Colorado Agricultural and Mechanical College, Fort Collins, Colorado; for studies on the Biota and Ecology of Certain Types of Montane Forests in Colorado, \$200.
5. To T. H. Goodspeed, Professor of Botany and Director of the Botanical Garden, University of California, Berkeley, California; for services of an artist in Completing Preparation of a Monograph on Nicotiana, \$550, contingent upon assurance that this aid will insure publication of same.

Total amount of grants-in-aid awarded October, 1946—\$2,200.

April 1947

1. To I. Amdur, Associate Professor of Physical Chemistry, Massachusetts Institute of Technology, Cambridge 39, Massachusetts; for expendable materials and for assistance in continuation of an experimental study of atomic and molecular interaction potentials, \$4,000.
2. To T. H. Bissonnette, Professor of Biology, Trinity College, Hartford 6, Connecticut; for continuation of a study of photoperiodism in animals, \$400.
3. To C. J. Goin, Instructor in Biology, University of Florida, Gainesville, Florida; for a genetic study on certain amphibia in Jamaica, \$350.
4. To H. B. Hitchcock, Associate Professor of Biology, Middlebury College, Middlebury, Vermont; for travel and expenses for a part of his study of the distribution and migration of *Myotis l. Lucifugus* and other bats, \$450.
5. To H. L. Movius, Jr., Assistant Curator of Palaeolithic Archaeology, Peabody Museum, Harvard University, Cambridge 38, Massachusetts; for a study of the significance and chronology of the Old Stone Age cultures within the territories of the U. S. S. R., \$1,500

Total amount of grants-in-aid awarded April, 1947—\$6,700.

Total number of grants for 1946-1947—10.

Total amount of grants for 1946-1947—\$8,900.

Respectfully submitted,

JOHN W. M. BUNKER, *Chairman*

May 14, 1947

REPORT OF THE AMORY PRIZE COMMITTEE

After considerable discussion of the deferred award to Dr. Laqueur it was voted to be the opinion of the present committee that the award voted to him in 1941 is now due, should be paid to him in any fashion he desires, and should be publicly announced.

Attention was given to the terms of the Amory award, considering the precise terms of this bequest, legal opinions regarding these terms, and understandings and precedents of the first Amory Prize Committee.

It was the consensus of opinion that the donor desired primarily that the awards be made for the encouragement of work of immediate therapeutic relevance but that such work being not available, work indirectly important to the treatment of disorders of the reproductive organs in human beings should be recognized. It was agreed that fundamental researches throwing light on the function of any of the reproductive organs has such importance.

It was further agreed that in case no single piece of work appeared to be of sufficiently great merit to justify awarding the entire prize to one individual, the available sum could most appropriately be divided into several lesser sums for individual awards.

It was the consensus that, other things being equal, awards to younger investigators rather than to established proponents would be within the letter of the terms of bequest and would most nearly promote the expressed purpose of the donor.

It was recognized that only work done in the preceding seven years was to be considered in assigning awards.

It was also decided that the funds should be awarded principally in the form of cash prizes, with some sort of relatively inexpensive scroll or certificate in addition. (The terms of the bequest permit this procedure.)

It was further agreed that the traveling expenses of the recipient, incurred in attendance upon a meeting of the Academy for receipt of the awards, would be paid and that they would be entertained at dinner on the evening of the said meeting.

The Secretary reported that an announcement of the awards with requests for nominations had been published throughout the world and that letters had been sent to several men in the field of genito-urology, asking for nominations.

Those nominated to date number twenty-nine. Recommendations for the next award will be made to

the Council after November 10, 1947 upon which date the current Septennium terminates.

Respectfully submitted,

ROY G. HOSKINS, *Secretary*

On the recommendation of the Treasurer, the Academy voted that the annual assessment for the year 1947-1948 for Resident Fellows be continued at fifteen dollars.

The following officers and committees were elected for the coming year:

Howard M. Jones.....	<i>President</i>
Roland G. D. Richardson....	<i>Vice-President for Class I</i>
Irving W. Bailey.....	<i>Vice-President for Class II</i>
Erwin N. Griswold.....	<i>Vice-President for Class III</i>
Donald Scott.....	<i>Vice-President for Class IV</i>
John W. M. Bunker.....	<i>Corresponding Secretary</i>
Isadore Amdur.....	<i>Recording Secretary</i>
Horace S. Ford.....	<i>Treasurer</i>
Frederick H. Pratt.....	<i>Librarian</i>
Taylor Starck.....	<i>Editor</i>

COUNCILLORS FOR FOUR YEARS

Joseph H. Keenan.....	Class I
Paul C. Mangelsdorf.....	Class II
Harvey H. Bundy.....	Class III
William G. Constable.....	Class IV

COMMITTEE ON PERMANENT SCIENCE FUND

John W. M. Bunker, *Chairman*

Roger Adams	Edward L. Moreland
Kirk Bryan	Julius A. Stratton
A. Baird Hastings	Payson S. Wild, Jr.

FINANCE COMMITTEE

Ralph E. Freeman	Henry P. Kendall
Jerome C. Hunsaker	Henry L. Shattuck

RUMFORD COMMITTEE

Harlow Shapley, *Chairman*

Percy W. Bridgman	Joseph H. Keenan
Arthur C. Hardy	Edwin H. Land
George R. Harrison	Francis O. Schmitt

C. M. WARREN COMMITTEE

Frederick G. Keyes, *Chairman*

Louis F. Fieser	Kenneth L. Mark
Grinnell Jones	Avery A. Morton
Charles A. Kraus	Walter C. Schumb

AMORY PRIZE COMMITTEE

Edwin B. Wilson, *Chairman*

William B. Castle	George W. Thorn
Roy G. Hoskins	George B. Wislocki
Gregory Pincus	S. Burt Wolbach

COMMITTEE OF PUBLICATION

Taylor Starck, *Chairman, ex officio*

Ernest H. Huntress.....	Class I
Kenneth V. Thimann.....	Class II

Thomas North Whitehead.....Class III
Kenneth J. Conant.....Class IV

COMMITTEE ON THE LIBRARY

Frederick H. Pratt, *Chairman, ex officio*
Raymond C. Archibald.....Class I
Charles A. Weatherby.....Class II
Francis N. Balch.....Class III
Henry B. Washburn.....Class IV

AUDITING COMMITTEE

Donald S. Tucker Thomas H. Sanders

HOUSE COMMITTEE

Charles M. Spofford, *Chairman*
Chester M. Alter H. Addington Bruce
John B. Wilbur

COMMITTEE ON MEETINGS

The President
The Recording Secretary
Bart J. Bok Arthur Clay Cope
Douglass V. Brown Henry B. Phillips

A new member was introduced by a sponsoring Fellow.

The following communication was presented:

Edward U. Condon: *The Work of the National Bureau of Standards.*

The meeting was dissolved at 10:15 P. M.

One Thousand Three Hundred and Twentieth Meeting

OCTOBER 8, 1947.—STATED MEETING

The Academy met at its House at 8:20 P. M.

The President in the Chair.

There were present forty-two Fellows.

The records of the meeting of May 14 were read and approved.

The Corresponding Secretary reported the receipt of letters accepting Fellowship from 28 newly elected Fellows: Howard Hathaway Aiken, David Lawrence Belding, Ruth Fulton Benedict, Richard Burgin, Thomas Dudley Cabot, Edward Uhler Condon, Paul Clifford Cross, John Dos Passos, Arnold Gesell, Sanford Burton Hooker, Mark DeWolfe Howe, Wilbur K. Jordan, Milton Edward Lord, Ralph Lowell, Charles Winters MacGregor, Lewis Mumford, Norman Burdett Nash, John Lord O'Brian, William Phillips, Francis Minot Rackemann, Fritz Jules Roethlisberger, James Stevens Simmons, Richard Mason Smith, Merrill Clary Sosman, Clark Conkling Stephenson, William Freeman Twaddell, Shields Warren, Sumner Welles; from 10 Foreign Honorary Members: Paal Berg, Hamilton Alexander

Rosskeen Gibb, Augustus Daniel Imms, P. Maheshwari, Edward Arthur Milne, Alf Erling Porsild, Meghnad N. Saha, Sir George Paget Thomson, Godfrey Hilton Thomson, Wong Wen-hao; also letters declining Fellowship from three newly elected Fellows: Hans Albrecht Bethe, Mildred McAfee Horton, Ivor Armstrong Richards.

He also announced that the Council had accepted with regret the resignations of: Walter F. Dearborn, IV, 1, Walter Hunter, IV, 1, L. Don Leet, II, 1, and that an error had been made in reporting the death of Louis E. Lapicque, Foreign Honorary Member, in the Council minutes of April 22.

The Fellows approved the action of the Council calling for a gift of \$250 with a suitable document of presentation to Mrs. M. F. Ball in recognition of more than twenty-five years of faithful service to the Academy.

New members were introduced by sponsoring Fellows.

The President introduced the newly appointed Executive Officer, Ralph W. Burhoe, who told the Fellows of his future plans and solicited their cooperation in helping him to vitalize the Academy along the lines recommended in the Report on the Present Status and Future of the Academy.

The principal business of the meeting was the consideration of the Report of a Special Committee on Revision of the Statutes. The President outlined the major changes which had been made in revising the Statutes. The Corresponding Secretary reported that the Council had approved the revised Statutes as circulated to the Fellows and moved that the Academy proceed to approve the revised statutes Chapter by Chapter. The following actions were taken:

a. Chapter I, approved.

b. Chapter II, approved after discussion in which it was pointed out that the revised Statutes permitted an increase in the number of Fellows to one thousand without actually requiring expansion beyond the previous limit of eight hundred members. During the discussion it was pointed out that it would be desirable to revise the nomenclature of the classes and sections in the near future.

c. Chapter III, approved.

d. Chapter IV, approved.

e. Chapter V, approved.

f. Chapter VI, approved.

g. Chapter VII, approved.

h. Chapter VIII, approved.

i. Chapter IX, approved with the substitution of "particular publications" for "special publications" at the end of Article 6. Several typographical errors were pointed out for correction. During this discussion the Fellows were urged to make greater use of the publication facilities of the Academy for presentation of original contributions. The Treasurer felt that the Academy funds were adequate to take care of considerable expansion of this portion of the Academy's publication activities.

j. Chapter X, approved.

k. Chapter XI, approved.

l. Chapter XII, approved. A motion was lost calling for substitution of "but not less than 27" for "in a meeting of not less than forty Fellows" in the last sentence of Article 5.

A motion to adopt the revised Statutes as amended was carried.

The Corresponding Secretary, as secretary of a Special Committee on Implementing the Revised Statutes, presented the following motion:

Moved: That the Statutes as amended and enacted October 8, 1947, shall become effective following the next annual election of officers in May 1948, except that:

(1) The Council, at its meeting on November 12, 1947, shall appoint an interim special Committee on Membership to serve until its successors are elected, as described in Chap. XI (Revised), Art. 1, Sec. ii, with duties as specified in Chap. III (Revised).

(2) The nomination and election of Fellows in May, 1948 shall be according to procedure as set forth in Chap. III (Revised).

(3) The election of officers and Standing Committees in May, 1948 shall conform to the revised Statutes.

(4) Chap. VII (Revised) and Chap. VIII (Revised) pertaining respectively to the Treasurer and the Librarian shall become effective immediately.

(5) Chap. IX, on the Editor and Publications, shall be put into effect after adoption of the revised Statutes.

(6) Chap. X, concerning the Council, shall become effective at once upon vote of the Council.

Mr. Shapley, chairman of the Rumford Committee, pointed out that due to the war, no Rumford premium had been awarded for four years and that it therefore might be necessary to award a premium retroactively to fulfill the conditions of the Rumford Trust calling for a biennial recommendation to the Council of a candidate for reception of the premium. During the discussion, Mr. Wyzanski pointed out that the Statutes did not call for Council approval of research grants in aid voted by the Rumford Committee.

A vote of thanks to the Special Committee on Revision of the Statutes was passed.

The meeting was dissolved at 9:50 P. M.

One Thousand Three Hundred and Twenty-first Meeting

NOVEMBER 12, 1947.—STATED MEETING

The Academy met at its House at 8:15 P. M.

The President in the Chair.

There were present forty-seven Fellows and thirty-three guests.

The records of the meeting of October 8 were read and approved.

The Corresponding Secretary reported the following actions of the Council:

1. The designation of Walter F. Dearborn, IV, 1, as Fellow Emeritus instead of acceptance of resignation as previously recorded.

2. The acceptance with regret of the resignation of Karl Sax, II, 2.

3. Authorization of the President to appoint an interim Committee on Membership to serve until the election of the regular Committee on Membership at the next annual election.

4. Authorization of a joint Committee of the American Academy of Arts and Sciences and the Boston Museum of Science which will cooperate with other groups to encourage interest in science among secondary school students.

The President invited the Fellows, on behalf of the Committee for the Arthur Dehon Little Memorial Lecture, to attend the Second Memorial Lecture on the topic, "Physics in the Contemporary World," at the Massachusetts Institute of Technology, November 25, 1947. The Lecturer, J. Robert Oppenheimer, is a Fellow of the Academy.

New members were introduced by sponsoring Fellows.

The following communications on *Problems in Evolution* were presented:

F. L. Whipple: *Some Current Trends of Thought Concerning Cosmic Evolution*.

A. S. Romer: *Advances in the Study of Organic Evolution*.

Bart J. Bok and F. L. Hisaw commented briefly on current research trends in astronomy and biology.

The meeting was dissolved at 10:20 P. M.

One Thousand Three Hundred and Twenty-second Meeting

DECEMBER 10, 1947.—STATED MEETING

The Academy met at the Georgian Room of the Statler Hotel at 7:00 P. M.

There was no scheduled business and the Corresponding Secretary acted as toastmaster in the absence of the President.

This meeting had been designated as the Third Annual Dinner Meeting and Ladies' Night. There were present, in addition to the speaker of the evening, fifty-five Fellows and their ladies.

The Corresponding Secretary briefly addressed the meeting on the traditions of the Academy in introducing the speaker of the evening, George D. Stoddard, President of the University of Illinois, whose communication was entitled: *Science Serves Two Masters*.

The meeting dissolved at 9:30 P. M.

One Thousand Three Hundred and Twenty-third Meeting

JANUARY 14, 1948.—STATED MEETING

The Academy met at its House at 8:20 P. M.

E. N. Griswold, Vice-President, in the Chair in the absence of the President.

There were present twenty-nine Fellows and six guests.

The records of the meetings of November 12 and December 10, 1947 were read and approved.

The Corresponding Secretary reported:

1. That A. W. Allen, II, 4, G. P. Baker, III, 3, and W. H. Clafin, Jr., III, 4, had accepted Fellowship and that G. A. Shajn, I, 1, had accepted Foreign Honorary Membership.

2. That the Council had designated as Fellows Emeriti: W. L. Evans, I, 3, and F. B. Talbot, II, 4.

3. That the President had appointed the following committees:

The Committee of Publication: K. B. Murdock to replace K. J. Conant.

The Committee on UNESCO: W. G. Constable, Hudson Hoagland, F. H. Taylor, P. S. Wild, Jr., and I. Amdur, chairman.

The Committee on Popular Lectures: E. N. Griswold, Ralph Lowell, and E. C. Kemble, chairman.

Interim Special Committee on Membership: Class I: J. L. Oncley, George Scatchard; Class II: C. A. Janeway, R. H. Wetmore; Class III: R. G. Caldwell, J. R. Killian, Jr.; Class IV: C. J. Ducasse, W. F. Twaddell.

4. That the Council had approved a recommenda-

tion of The Rumford Committee granting \$550 to W. F. Meggers of the National Bureau of Standards.

A new member was introduced by a sponsoring Fellow.

The following communication was presented:

W. J. Cunningham: *New England Transportation and Its Relation to the New England Economy*.

Following the discussion of the communication, A. P. Usher spoke briefly on recent research trends in economics.

The meeting was dissolved at 9:45 P. M.

One Thousand Three Hundred and Twenty-fourth Meeting

FEBRUARY 11, 1948.—STATED MEETING

The Academy met at its House at 8:20 P. M.

The President in the Chair.

There were present forty-four Fellows and one hundred and thirty guests.

The records of the meeting of January 14 were read and approved.

The Corresponding Secretary stated that there were no Council actions to report.

Two new members were introduced by sponsoring Fellows.

The following communication was presented:

John von Neumann: *Electronic Methods of Computation*.

The meeting was dissolved at 9:50 P. M.

One Thousand Three Hundred and Twenty-fifth Meeting

MARCH 10, 1948.—STATED MEETING

The Academy met at its House at 8:20 P. M.

The President in the Chair.

There were present fifty-seven Fellows and one hundred and nineteen guests including A. L. von Muralt, President of the Swiss Academy of Natural Sciences.

The records of the meeting of February 11 were read and approved.

The Corresponding Secretary reported that the Council had approved appropriations totaling \$19,405 for salaries, meetings and maintenance for the next fiscal year and had recommended the sum of \$15.00 for the next annual assessment.

The President announced the appointment of a Nominating Committee consisting of: R. E. Freeman, III, 3, chairman; G. J. Esselen, I, 3; C. S. Keefer, II, 4; W. O. Ault, IV, 2.

Two new members were introduced by sponsoring Fellows.

The communication entitled, *Peacetime Uses of Atomic Energy* was presented by three speakers as follows:

I. *Problems of Power Development*: E. R. Gilliland, Professor of Chemical Engineering, Massachusetts Institute of Technology.

II. *Research Problems in the Physical Sciences*: C. D. Coryell, Professor of Chemistry, Massachusetts Institute of Technology.

III. *Research Problems in the Medical Sciences*: F. D. Moore, Assistant Professor of Surgery, Harvard Medical School.

The meeting was dissolved at 10:00 P. M.

One Thousand Three Hundred and Twenty-sixth Meeting

APRIL 14, 1948.—STATED MEETING

The Academy met at its House at 8:23 P. M.

The President in the Chair.

There were present twenty-three Fellows and thirty-seven guests.

The records of the meeting of March 10 were read and approved.

The Recording Secretary, in the absence of the Corresponding Secretary, read the list of grants from the Permanent Science Fund made by the Council.

A new member was introduced by a sponsoring Fellow.

The following communication was presented:

W. G. Constable: *The Painter's Workshop*.

The meeting was dissolved at 9:45 P. M.

One Thousand Three Hundred and Twenty-seventh Meeting

MAY 12, 1948.—ANNUAL MEETING

The Academy met at its House at 8:26 P. M.

The President in the Chair.

There were present fifty-three Fellows and about sixty guests.

The records of the meeting of April 14 were read and approved.

In the absence of the Chairman of the Rumford Committee, Harlow Shapley, Percy W. Bridgman introduced the Rumford medallist for 1945, Edwin H. Land. The President presented Mr. Land with a gold and silver medal in conformity with the conditions of the award.

The communications entitled *Theory and Application of Synthetic Polarizing Sheets* and *A Brief Description of the Functional Approach to One-step Photography* were presented by Mr. Land.

The Corresponding Secretary presented the following budget items which were approved by the Fellows:

\$19,405 for items as presented at the March meeting; \$800 appropriation for addressograph and accessories; \$15 annual assessment for the year 1948-1949.

The President read the following report on deaths, resignations, and the status of the membership:

I regret to have to report the following deaths: Twenty-three Fellows and three Fellows Emeriti—Elliott Carr Cutler (II: 4), Rollins Adams Emerson (II: 2), Henry Thatcher Fowler (FE IV: 2), James Walter Goldthwait, (II: 1), Evarts Boutell Greene (IV: 2), Robert Almer Harper (II: 2), Reid Hunt (FE II: 4), Ellsworth Huntington (II: 1), Dunham Jackson (I: 1), Henry James (IV: 4), Grinnell Jones (I: 3), Charles Atwood Kofoid (II: 3), Frank Rattray Lillie (II: 3), Thomas William Lamont (III: 4), Alfred Church Lane (II: 1), Burton Edward Livingston (II: 2), William Ralph Maxon (II: 2), James Vance May (III: 4), John Bassett Moore (III: 2), James Hugh Ryan (IV: 1), William Isaac Thomas (III: 3), Edward Sampson Thurston (III: 1), Alfred North Whitehead (FE I: 1), Herbert Percy Whitlock (II: 1), Frank Clifford Whitmore (I: 3), Clark Wissler (IV: 3); Eleven Foreign Honorary Members—Frederick Orpen Bower (II: 2), Johannes N. Brönsted (I: 3), Léon Duguit (III: 1), Henri Guy (IV: 4), Godfrey Harold Hardy (I: 1), Paul Hazard (IV: 4), Gustaf Adolf Frederik Molengraaff (II: 1), Max Planck (I: 2), Rudolf Stammler (III: 1), S. Rudolph Steinmetz (III: 3), Peter Bernhardovich Struve (III: 3).

Four Fellows have resigned: Walter Samuel Hunter (IV: 1), Lewis Don Leet (II: 1), Robert P. Patterson (III: 1), Karl Sax (II: 2).

Nine Fellows have been classed as Emeriti: As of May 1, 1947—William James Cunningham (III: 3), Walter Fenno Dearborn (IV: 1), William Lloyd Evans (I: 3), George La Piana (IV: 2), Elton Mayo (III: 3), Hervey Woodburn Shimer (II: 1), Henry Bradford Washburn (IV: 1); As of May 1, 1948—Robert Bayley Osgood (II: 4), Fritz Bradley Talbot (II: 4).

In May 1947, the election by the Council of thirty-four Fellows and thirteen Foreign Honorary Members was announced to the Academy; all except three Fellows (Hans Albrecht Bethe; Mildred McAfee Horton; Ivor Armstrong Richards) and one Foreign Honorary Member (I. M. Vinogradov) accepted election.

The roll now includes 762 Fellows, 32 Fellows Emeriti, and 117 Foreign Honorary Members (exclusive of those elected in 1948).

The following annual reports were read and approved:

REPORT OF THE TREASURER

(Extract)

*RECEIPTS, 1947-1948

Academy, General:

Investment Income	\$32,042.51
Less: Income to Special Funds	15,276.80
	\$16,765.71
Use of Facilities	2,403.96
Assessments and Admission Fees	6,602.50
Transfer of Unexpended Appropriations	676.63
	\$26,448.80

Mabel S. Agassiz Fund:

Investment Income	108.80
-------------------	--------

Amory Prize Committee:

Investment Income	3,987.00
-------------------	----------

Kennelly Fund:

Investment Income	82.00
-------------------	-------

Library Sale Fund:

From Linda Hall Library Trustees	180,000.00
----------------------------------	------------

Life Membership Fund:

From Daniel L. Marsh and Sarah Wambaugh	400.00
---	--------

Permanent Science Fund:

Boston Safe Deposit and Trust Co., Trustee	\$11,894.05
Return of Grant	350.00
Investment Income	2,975.00
	15,219.05

Publications Committee:

Investment Income	\$2,818.00
Sale of Publications	512.24
Lake Publications	662.50
	3,992.74

Rumford Committee:

Investment Income	\$4,305.00
Return of Grant	43.77
	4,348.77

School Science Fund:

Boston Society of Natural History	250.00
-----------------------------------	--------

Special House Alterations Fund:

Fire Loss and Sales	724.00
---------------------	--------

C. M. Warren Committee:

Investment Income	1,001.00
-------------------	----------

Total Receipts \$236,562.16

* Excluding sales of securities.

*EXPENDITURES, 1947-1948

Academy, General:

Salaries and Pensions	\$9,067.02
Meetings and General Administration	3,350.74
House Maintenance	3,976.64
President's Expense	143.80
Treasurer's Expense	713.81
Special Appropriations:	
Alterations	\$5,071.00
School Science Fund	250.00
	5,321.00
	\$22,573.01

Mabel S. Agassiz Fund:

For Meetings	108.80
--------------	--------

Amory Prize:

Deferred Award	\$4,300.00
Expense	157.27
	4,457.27

Carnegie Corporation, for Visual Arts Conference:

	97.34
--	-------

Library Sale Fund:

Boxes, Express, Storage, etc.	3,077.46
-------------------------------	----------

Permanent Science Fund:

Grants	\$6,700.00
Expense	5.39
	6,705.39

Publications Committee:

General	\$944.75
Lake	10.59
	955.34

Rumford Committee:

Grants	\$1,300.00
Medals	591.49
Expense	160.50
	2,051.99

School Science Fund:

	63.63
--	-------

Special House Alterations Fund:

	8,040.51
--	----------

C. M. Warren Committee:

Grants	750.00
--------	--------

Total Expenditures \$48,880.74

REPORT OF THE RUMFORD COMMITTEE

Three grants in aid of research have been made during the year 1947-1948 as follows:

To Dr. Stefan L. Piotrowski, of Cracow, Poland, \$500, to assist in the construction of a photoelectric photometer for work on eclipsing binaries in cooperation with the International Astronomical Union's Panel on Eclipsing Binaries.

To Dr. William F. Meggers, of the National Bureau of Standards, Washington, D. C., \$550, to assist in spectroscopic researches at the Bureau of Standards by Professor Catalán of Madrid, Spain.

* Excluding purchases of securities.

To Dr. Francis Birch, of the Harvard Geophysical Department, \$400, to assist in preparing conductivity specimens from rocks from the Alva B. Adams Tunnel.

Awards of the Rumford Premiums and Medals were made as follows: for 1945 to Edwin H. Land for his pioneer work on Polaroid and its applications; for 1947 to E. Newton Harvey of Princeton, New Jersey, for his work on animal luminescence.

The Assistant Treasurer of the American Academy reports a balance on hand on March 8, 1948, of \$20,064.89.

The estimated investment income for 1948-1949 is \$4,535. The total available for appropriation is \$24,599.89.

Respectfully submitted,
HARLOW SHAPLEY, *Chairman*

May 12, 1948

REPORT OF THE CYRUS M. WARREN COMMITTEE

The Committee had available for grants during 1947-1948 the sum of \$1000.00 which amount was voted for awards at the meeting on March 12, 1947.

The following grants were made, after consideration by the Committee, of the applications submitted:

To Doctor Charles L. Bickel of the Phillips Exeter Academy, a grant of \$150.00 to provide supplies and perhaps apparatus for research problems in organic chemistry.

To Professor L. V. Coulter of Boston University, a grant of \$300.00 for the construction of apparatus in connection with a study to determine the effect of molecular structure on hydrogen bond strengths.

To Professor A. E. Martell of Clark University, a grant of \$300.00 to assist in the purchase of apparatus for use in an investigation involving electrical conductivity measurements of dilute non-aqueous solutions.

A letter was received from Professor Martell reporting on the purchase of apparatus and the progress of the research program, and expressing his thanks and that of Clark University to the Cyrus M. Warren Committee for the assistance.

A letter from Doctor Bickel reports on the progress of his research project. One problem has been completed and a manuscript based on the work has been accepted for publication.

Respectfully submitted,
FREDERICK G. KEYES, *Chairman*

May 12, 1948

REPORT OF THE COMMITTEE OF PUBLICATION

The Committee has held only one meeting during the year though there was some exchange of information and opinion by correspondence and orally.

No monographs or books were submitted for publication during the year.

This is the first year under the new Statutes which require the publication of a Summer and a Winter number of the Proceedings, each of which is to include certain material. As the Academy did not begin to operate under the new Statutes until the fall, the Winter number, now in press, will be distributed to members only this month. The Summer number, part of which is in type, should be ready in September. These two numbers will conclude Volume 76. Hereafter the Winter number will appear as soon as possible after the December meeting, the Summer number after the Annual meeting.

Beginning with January, 1948, five monthly numbers of the Bulletin have been issued. In the ensuing year the statutory number of eight will be published. All the work entailed by this publication has been accomplished by the Executive Officer of the Academy, Mr. Ralph Burhoe.

The manuscript of a *Study of Massachusetts Facilities for Child Health*, mentioned in the last report, has not yet been submitted.

The expenditures for 1947-1948 were only \$772.46. However the cost of two numbers of the Bulletin and of the two numbers of the Proceedings will appear in the statement for 1948-1949. The new year will also see the full volume of eight Bulletins that we estimate will cost about \$1,100. The expenses for the past year were therefore abnormally small. The reserve balance of \$11,832 and the estimated \$2,750 income from investments provide a substantial backlog to meet unforeseen expenses or increases in the printing costs. We may also count on a certain amount from sales of publications. In the past year this item was \$429.07 and we may expect the sales to continue at approximately the same rate. Funds are therefore available for the publication of all acceptable manuscripts that are likely to be presented within the coming twelve months.

The Editor has discussed with the Publication Committee and the Executive Officer the advisability of soliciting manuscripts for publication. We feel that the Fellows have gotten out of the habit of thinking of the Academy when they have manuscripts for publication. We propose to call the attention of the members to the advantages of publication in the Proceedings and the Memoirs through a note in the October number of the Bulletin. We should constantly have on hand material for one full number of the Proceedings. This would not delay publication as long as it is delayed by most professional journals, some of which are two years or more in arrears. Our aim is to achieve prompt and regular issuance of the Proceedings and to cover all the fields of interest in rotation. Obviously this goal cannot be attained unless manuscripts are regularly submitted from all classes and sections of the Academy.

Respectfully submitted,
TAYLOR STARCK, *Chairman*

May 12, 1948

REPORT OF THE LIBRARY COMMITTEE

Following the sale, so skillfully organized by Mr. Metcalf, of our main holdings to the Linda Hall Library of Kansas City, the small remainder of some 650 early volumes has been disposed as follows:

The greater part—a bequest of our first President, Governor James Bowdoin—has been deposited at Bowdoin College, where much valuable Bowdoin material is already attractively housed. The Boston Athenaeum, where for many years our library had its home, is again the custodian of the great folio sets given by John Adams and bequeathed by Benjamin Franklin, respectively. Further, a number of 18th century editions of the classics given by Francis Vergnies de Bonischere, once a prominent physician of Newburyport, are now at the Essex Institute of Salem.

It is believed the above assignments are such as to afford especially appropriate settings for these permanent loans, and at the same time to render them of most use to scholars. Our reading room will still retain a few shelves of books representative of miscellaneous early donors.

Mrs. Mabel Frothingham Ball's retirement after twenty-five years as Assistant Librarian calls for more than usual notice from the Academy. Her service, not only as a trained librarian but as a general executive secretary, has been uniformly faithful—at times even in the face of almost mortal illness. The detailed grasp of Academy affairs, past and present, that she acquired has of late been of invaluable aid in the institution of our new executive department.

With this occasion the traditional library administration comes to an end; but it gratifying to note the perpetuation of the post of Librarian, under which a number of important functions related to income and outgo of published material are bound to call for continued attention. The retiring Librarian would express to his fellow members of the Committee his utmost gratitude for their unstinted helpfulness and generous counsel during these years of transition.

Respectfully submitted,

FREDERICK HAVEN PRATT, *Chairman*

May 12, 1948

REPORT OF THE HOUSE COMMITTEE

The use of the House by other organizations, as recommended by the Mather Commission report, has increased greatly during the year. An indication of this is shown in the increase from \$205, for the previous year, to \$2,404, in the present year, in re-imbursement for the use of our facilities. The Co-operative Broadcasting Council of the Lowell Institute has continued to occupy 1,200 square feet on the fourth floor, and the second and third floors of the stacks are still being occupied by the Library of the Boston Museum of Science. The organizations in addition to the Academy using the facilities for meetings are listed below:

	<i>Number of Meetings</i>
American Association of University Women.....	1
American Institute of Decorators.....	3
Antiques Committee, Massachusetts State Federation of Women's Clubs.....	3
Boston College Institute of Adult Education.....	15
Boston Mineral Club.....	3
Boston Society of Civil Engineers.....	2
Boston Teachers Union.....	9
Brookline Bird Club.....	2
Children's Museum.....	4
French Center of New England.....	15
Herbert Read Lecture (Institute of Contemporary Art, M. I. T., etc.).....	1
Institute of Religious and Social Studies.....	6
Joyce Kilmer Post, American Legion.....	9
Lowell Institute Co-operative Broadcasting Council	1
New England Botanical Club.....	9
New England Farm and Garden Association.....	7
Pan American Society.....	3
Radcliffe Alumnae.....	1
Soil Conservation Society.....	1

Total number of meetings (of 19 societies)..... 95

About 7,500 persons attended meetings at the Academy held by outside organizations.

Besides the regular meetings of the Academy, there have been about 50 meetings of various committees and sub-committees of the Academy at the House.

During the year the remainder of the library books sold to the Linda Hall Library were shipped and the top three floors of the library stack wing are now essentially empty of our books. During the year a petition for use of these top three floors by an outside organization was declined on account of expense involved and the uncertainty of the Academy's own needs.

Further alterations and renovations of the House continued. The Reading Room was cleaned and painted, and new lighting was installed; the two front rooms on the first floor were converted to office space; the main portion of the first floor was altered to make it suitable for an exhibit hall; the closet room adjacent to the Reading Room was equipped with a sink to make it more useful in connection with serving refreshments and buffet style meals in the Reading Room; the former office of the Librarian was converted to a conference room.

The expenditures of the House Committee for regular operations totalled \$6,772.65, as listed below:

<i>House Maintenance</i>	
Coal.....	\$1,024.08
Gas.....	22.05
Electricity.....	900.74
Elevator.....	545.34
Water.....	39.00
Equipment.....	298.45
Supplies and Repairs.....	600.97

Fire Insurance.....	\$543.60
Telephone.....	262.94
Caretaker.....	1,933.07
Pensions.....	600.00
Miscellaneous.....	2.41
Total.....	\$6,772.65

The appropriation for the House Committee was \$5,600, in addition to which there was an income of \$2,403.96 for the use of facilities, making a total of \$8,003.96, and leaving unexpended, \$1,231.31.

For special alterations there was expended \$8,040.51. Made available for this was a total of \$12,477.73, consisting of the following:

Balance remaining of first appropriation for special alterations.....	\$6,682.73
Receipts for sale of stacks.....	500.00
Receipts for fire loss of equipment loaned..	224.00
Appropriation by Council for further alterations.....	5,071.00
Total.....	\$12,477.73

This leaves \$4,437.22 unexpended balance of the funds for special alterations. The Committee revised Section 4 of the Rules for the Use of the House to read as follows:

"Fellows may use the Committee Room on the third floor without charge. For the use of this room by others, the charge will be \$5.00. For the use of the Assembly Hall, a charge of \$15.00 will be made for each occasion; for the Reading Room, there will be a charge of \$10.00 if no refreshments are served; or \$15.00 if there are refreshments. An additional charge of \$5.00 will be made for each hour or fraction of an hour during which the rooms are occupied after 11 P. M. The House Committee is authorized, however, to reduce the charges in special cases."

In closing I wish to pay tribute to the excellent service rendered by our Executive Officer. Mr. Burhoe, whose energy, ability and vision simplify greatly the work of the House Committee.

Respectfully submitted,

CHARLES M. SPOFFORD, *Chairman*

May 12, 1948

REPORT OF THE COMMITTEE ON THE PERMANENT SCIENCE FUND

The Committee on the Permanent Science Fund awarded eight grants-in-aid for a total of \$4,400. during the fiscal year 1947-1948, as follows:

1. To Elso S. Barghoorn, Assistant Professor of Botany and Curator of Paleobotany, Harvard University, Cambridge 38, Mass.; for a paleobotanical study of lignite in Vermont, \$600.

2. To Charles T. Brues, Professor of Entomology, Emeritus, Biological Laboratories, Harvard University, Divinity Avenue, Cambridge 39, Mass., for further classification of insects in amber, \$615.

3. To Lincoln Constance, University of California, Visiting Professor at Harvard University, Acting Director of Gray Herbarium, Cambridge 38, Mass.; for travel for field study in Texas on the mode of origin of certain wild plant species, \$350.

4. To Kenneth J. Conant, School of Design, Harvard University, Cambridge 38, Mass.; for aid in a three dimensional study of a Mediaeval Monastic group which formerly existed at Cluny in Burgundy, \$425.

5. To Hallam L. Movius, Jr., Peabody Museum, Harvard University, Cambridge 38, Mass.; for a supplementary grant for his study of Paleolithic Culture in the U. S. S. R., publication of which has been assured from another source, \$750.

6. To Bernard F. Riess, Department of Animal Behavior, American Museum of Natural History, 135 Cushman Road, Scarsdale, New York; for aid in a study of relation of diet to susceptibility to audiogenic and stress shock, \$1,000.

7. To Alexander Forbes, Harvard Medical School, 25 Shattuck Street, Boston, Mass.; for continuation of study of refractory phase in cerebral mechanism, \$300.

8. To William M. Ingram, Department of Zoology, Mills College, Oakland 13, California; for completion of a study of "Fossil and Recent Cypraeidae of the Eastern Regions of the Americas," \$360.

The Committee, for its own guidance, has formulated certain principles in respect to recommending grants-in-aid, as follows.

In general, it favors granting support to individuals rather than to organizations, although grants are permissible to public or private associations, societies or institutions.

Special consideration is deemed to be appropriate for projects on new frontiers of science, those which lie between or include two or more recognized fields, and to those proposed by investigators who may be on the threshold of investigational careers, or who are handicapped by lack of resources.

The Committee ordinarily does not approve grants for the purchase of non-expendable equipment of a type which can usually be expected of an institutional laboratory, but does recognize that for special purposes, regular or special equipment may be needed and approvable.

The Committee believes that the purpose of the Fund can best be served by something of the order of 10 grants per year, not exceeding \$1,500 each, although it is aware of the accumulated funds which make possible support of a limited number of large projects.

Respectfully submitted,

JOHN W. M. BUNKER, *Chairman*

May 12, 1948

REPORT OF THE AMORY PRIZE COMMITTEE

The Committee on the Amory Prize met five times:

(1) May 7, 1947. A report was prepared for submission to the Council recommending the Prize to six persons, viz., Drs. Dorfman, Huggins, Kenyon,

Kochakian, Marrian, and Olive Smith. The report was rejected by the Council on the ground that the Septennium did not expire until November 10, 1947, and recommendations were not in order until after that date.

(2), (3) January 14 and 26, 1948. The Committee took up the rejected report, reread the Amory will, decided to place more emphasis on studies close to therapy, drew up a list of persons who should be considered for the prize, and parcelled out among the members those whose contributions each should investigate.

(4) February 11, 1948. The Committee members reported their findings; there was ample discussion, a list of six persons, viz., Drs. Huggins, Marrian, Waksman, Papanicolaou, Kolff and Gutman (who had the cooperation of his wife) was adopted in that order but without prejudice or preference as to relative merit; a report to the Council was prepared recommending that the prize be equally divided between these six and that certain arrangements be made as tokens of the esteem in which they were held by the Academy. The report was referred by the Council for legal advice, upon receipt of which it was recommitted to the Committee with a copy of the legal opinion.

(5) May 5, 1948. The Committee members studied and discussed the legal opinion, in which they were much disappointed, and formulated a new report recommending the same six persons for the prize and leaving to the Council the determination of the amounts of the prizes and the arrangements for distributing them. The amount available for the prizes is reported to be \$23,289 less whatever may be appropriately deducted for administrative expenses.

Respectfully submitted,
May 12, 1948 EDWIN B. WILSON, *Chairman*

It was voted to send a note of appreciation to Frederick H. Pratt for his long service to the Academy as Librarian.

The annual election of officers and committees was held. The Fellows proposed by the Nominating Committee were elected to office as follows:

Howard M. Jones	.....	<i>President</i>
Roland G. D. Richardson	.....	<i>Vice-President for Class I</i>
Irving W. Bailey	.....	<i>Vice-President for Class II</i>
Robert B. Stewart	.....	<i>Vice-President for Class III</i>
Donald Scott	.....	<i>Vice-President for Class IV</i>
John W. M. Bunker	.....	<i>Secretary</i>
Horace S. Ford	.....	<i>Treasurer</i>
Henry R. Viets	.....	<i>Librarian</i>
Taylor Starek	.....	<i>Editor</i>

COUNCILLORS TO SERVE FOUR YEARS

Isadore Amdur	.....	<i>Class I</i>
Arlie V. Bock	.....	<i>Class II</i>
Keyes DeW. Metcalf	.....	<i>Class III</i>
Crane Brinton	.....	<i>Class IV</i>

HOUSE COMMITTEE

Chester M. Alter, <i>Chairman</i>	
H. Addington Bruce	John B. Wilbur

COMMITTEE ON MEMBERSHIP

The President, *Chairman, ex officio*

<i>To serve for one year</i>		<i>To serve for two years</i>
J. Lawrence Oncley	<i>Class I</i>	George Scatchard
Charles A. Janeway	<i>Class II</i>	Ralph H. Wetmore
Robert G. Caldwell	<i>Class III</i>	James R. Killian, Jr.
Curt J. Ducasse	<i>Class IV</i>	W. Freeman Twaddell

COMMITTEE ON MEETINGS

The President, *Chairman, ex officio*

The Secretary, *ex officio*

Bart J. Bok	Arthur Clay Cope
Douglass V. Brown	Henry B. Phillips

COMMITTEE ON FINANCE

The Treasurer, *Chairman, ex officio*

Ralph E. Freeman	Henry P. Kendall
Jerome C. Hunsaker	Henry L. Shattuck

AUDITING COMMITTEE

Thomas H. Sanders	Donald S. Tucker
-------------------	------------------

COMMITTEE ON PUBLICATION

The Editor, *Chairman, ex officio*

Ernest H. Huntress	Kenneth V. Thimann
Kenneth B. Murdock	Thomas North Whitehead

PERMANENT SCIENCE FUND COMMITTEE

John W. M. Bunker, *Chairman*

Kirk Bryan	Edward L. Moreland
Gustavus J. Esselen	Julius A. Stratton
A. Baird Hastings	Payson S. Wild, Jr.

RUMFORD COMMITTEE

Harlow Shapley, *Chairman*

Percy W. Bridgman	Joseph H. Keenan
Arthur C. Hardy	Edwin H. Land
George R. Harrison	Francis O. Schmitt

C. M. WARREN COMMITTEE

Frederick G. Keyes, *Chairman*

Edwin J. Cohn	Charles A. Kraus
Louis F. Fieser	Avery A. Morton
Hudson Hoagland	Walter C. Schumb

AMORY PRIZE COMMITTEE

Edwin B. Wilson, *Chairman*

William B. Castle	George W. Thorn
Roy G. Hoskins	George B. Wislocki
Gregory Pincus	S. Burt Wolbach

New Fellows and Foreign Honorary Members were elected to the Academy as follows:

FELLOWS

CLASS I, SECTION 1

William Ted Martin	Cambridge
Hassler Whitney	Cambridge
Oscar Zariski	Cambridge

CLASS I, SECTION 2

Enrico Fermi..... Chicago, Ill.
 Bruno Benedetto Rossi..... Cambridge
 Julian Seymour Schwinger..... Cambridge
 Victor Frederick Weisskopf..... Cambridge

CLASS I, SECTION 3

Carl Ferdinand Cori..... St. Louis, Mo.
 Charles duBois Coryell..... Cambridge
 Vincent du Vigneaud..... New York, N. Y.
 Robert Burns Woodward..... Cambridge

CLASS I, SECTION 4

John Chipman..... Cambridge
 Ivan Alexander Getting..... Cambridge
 Edwin Richard Gilliland..... Cambridge
 Hoyt Clarke Hottel..... Cambridge
 William Henry McAdams..... Cambridge
 Thomas Kilgore Sherwood..... Cambridge
 Theodor von Kármán..... Pasadena, Cal.
 Walter Gordon Whitman..... Cambridge

CLASS II, SECTION 1

Arthur Francis Buddington..... Princeton, N. J.
 Adolph Knopf..... New Haven, Conn.
 George Gaylord Simpson..... New York, N. Y.

CLASS II, SECTION 2

Edward Sears Castle..... Cambridge
 William Jacob Robbins..... New York, N. Y.
 William Randolph Taylor..... Ann Arbor, Mich.
 Frits Warmolt Went..... Pasadena, Cal.

CLASS II, SECTION 3

Edward Adelbert Doisy..... St. Louis, Mo.
 Wallace Osgood Fenn..... Rochester, N. Y.
 Herbert Spencer Gasser..... New York, N. Y.
 Edmund Newton Harvey..... Princeton, N. J.
 Hubert Bradford Vickery..... New Haven, Conn.
 George Wald..... Cambridge
 Sewall Wright..... Chicago, Ill.

CLASS II, SECTION 4

Francis Gilman Blake..... New Haven, Conn.
 Allan Macy Butler..... Boston
 Edward Delos Churchill..... Boston
 John Rock..... Boston

CLASS III, SECTION 1

Charles Allerton Coolidge..... Boston

CLASS III, SECTION 2

William Lockhart Clayton..... Washington, D. C.
 Howard Eugene Wilson..... New York, N. Y.

CLASS III, SECTION 3

Richard Bissell, Jr..... Cambridge
 Bishop Carleton Hunt..... Boston

CLASS III, SECTION 4

Erwin Dain Canham..... Boston
 Charles Woolsey Cole..... Amherst
 Robert Cutler..... Boston

Herbert John Davis..... Northampton
 Dwight David Eisenhower..... New York, N. Y.
 Carl Stephens Ell..... Boston
 Francis Calley Gray..... Boston
 Paul Gray Hoffman..... Washington, D. C.
 Carl Tilden Keller..... Boston
 David Eli Lilienthal..... Washington, D. C.
 Alfred Pritchard Sloan, Jr..... New York, N. Y.
 Henry Merritt Wriston..... Providence, R. I.

CLASS IV, SECTION 1

Rudolph Carnap..... Chicago, Ill.
 Frederick May Eliot..... Boston
 Arthur Edward Murphy..... Ithaca, N. Y.
 Hans Reichenbach..... Los Angeles, Cal.
 Alfred Tarski..... Berkeley, Cal.

CLASS IV, SECTION 2

Margaret Mead..... New York, N. Y.

CLASS IV, SECTION 3

Bernard Bloch..... New Haven, Conn.
 Leonard Bloomfield..... New Haven, Conn.
 Yuen Ren Chao..... Berkeley, Cal.
 Berthold Louis Ullman..... Chapel Hill, N. C.

CLASS IV, SECTION 4

Bartlett Harding Hayes, Jr..... Andover
 Edward Hopper..... New York, N. Y.
 John Marin..... Cliffside Park, N. J.
 Thomas Munro..... Cleveland, O.
 Erwin Panofsky..... Princeton, N. J.
 Bruce Simonds..... Hamden, Conn.
 John Sloan..... New York, N. Y.

FOREIGN HONORARY MEMBERS

CLASS I, SECTION 2

Max von Laue..... Göttingen
 Arnold Sommerfeld..... Munich

CLASS I, SECTION 3

Sir Robert Robinson..... Oxford
 The Svedberg..... Upsala

CLASS II, SECTION 2

P. Boysen-Jensen..... Copenhagen
 Birbal Sahni..... Lucknow, India

CLASS II, SECTION 3

Charles Herbert Best..... Toronto
 Archibald Gowanlock Huntsman..... Toronto

CLASS III, SECTION 1

Léon Julliot de la Morandière..... Paris

CLASS III, SECTION 2

José d'Almada..... Lisbon

CLASS IV, SECTION 4

Jean-Marie Carré..... Paris
 Diego Rivera..... Coyacan, Mexico
 Jan Hendrik Scholte..... Amsterdam

The meeting dissolved at 10:07 P. M.

INDEX

A. INDEX OF AUTHORS AND TITLES OF PAPERS

- Amdur, I., The Scattering of High Velocity Neutral Particles. I.
- Bridgman, P. W., The Compressions of Sixty-one Solid Substances to 25,000 kg/cm², Determined by a New Rapid Method, 9
- The Compression of 39 Substances to 100,000 kg/cm², 55
- The Compression of Twenty-one Halogen Compounds and Eleven Other Simple Substances to 100,000 kg/cm², 1
- The Linear Compression of Various Single Crystals to 30,000 kg/cm², 89
- Rough Compressions of 177 Substances to 40,000 kg/cm², 71
- Carpenter, F. M., Lower Permian Insects from Oklahoma. Part 1. Introduction and the Orders Megasecoptera, Protodonata, and Odonata, 25
- Compression of Sixty-one Solid Substances to 25,000 kg/cm², Determined by a New Rapid Method, 9
- Compression of 39 Substances to 100,000 kg/cm², 55
- Compression of Twenty-one Halogen Compounds and Eleven Other Simple Substances to 100,000 kg/cm², 1
- Glick, C. F. (co-author), The Scattering of High Velocity Neutral Particles. I., 101
- Linear Compression of Various Single Crystals to 30,000 kg/cm², 89
- Lower Permian Insects from Oklahoma. Part 1. Introduction and the Orders Megasecoptera, Protodonata, and Odonata, 25
- Pearlman, H. (co-author), The Scattering of High Velocity Neutral Particles. I., 101
- Rough Compressions of 177 Substances to 40,000 kg/cm², 71
- Scattering of High Velocity Neutral Particles. I., 101

B. INDEX TO AFFAIRS OF THE AMERICAN ACADEMY OF ARTS AND SCIENCES

- American Council of Learned Societies, approval of amendments, 128
- Agassiz, gifts, 128
- Annual meetings, see Meetings, Annual
- Appropriations: 1945-46, 124; 1946-47, 131; 1947-48, 140; 1948-49, 150, 151
- Policy changed, 140
- Assessments: 1945-46, 128; 1946-47, 136; 1947-48, 147; 1948-49, 151
- Assistant Librarian, retirement of, 148, 154
- Barbour Fund, 141
- Bulletin, established, 153
- Charter, amendment of, 140
- Committees, list of: 1945-46, 129; 1946-47, 136; 1947-48, Vol. 76 (3), i, 147; 1948-49, 121, 156
- Amory Prize: 1947-48, 147; 1948-49, 156
- Made Standing Committee, 137
- Report of: 1947, 147; 1948, 155
- Auditing: 1945-46, 129; 1946-47, 137; 1947-48, 148; 1948-49, 156
- Biographical Notices, 1945-46, 129
- Finance: 1945-46, 129; 1946-47, 136; 1947-48, 147; 1948-49, 156
- Report of, see Treasurer
- House: 1945-46, 129; 1946-47, 137; 1947-48, 148; 1948-49, 156
- Alterations, 135, 145, 154
- Custodian, 135
- Lowell Institute Cooperative Broadcasting Council office, 145
- Report of: 1945, 127; 1946, 135; 1947, 145; 1948, 154
- Rules revised, 146, 155
- Library: 1945-46, 129; 1946-47, 137; 1947-48, 148
- Report of: 1945, 127; 1946, 135; 1947, 144; 1948, 154
- Sale of Library, 135
- Mather, see Committee on Present Status and Future of Academy
- Meetings: 1945-46, 129; 1946-47, 137; 1947-48, 148; 1948-49, 156
- Membership, 1948-49, 156
- Interim Special Committee, 149, 150
- Nominating: 1945, 125; 1946, 131; 1947, 140; 1948, 150
- Permanent Science Fund: 1946-47, 136; 1947-48, 147; 1948-49, 156
- Grants: 1944, 123; 1946, 132; 1946-47, 146; 1947-48, 155
- Made Standing Committee, 128
- Report of: 1946, 136; 1947, 146; 1948, 155
- Policy and Resources, 1945-46, 129
- Discontinued, 129
- Popular Lectures, 150
- Present Status and Future of Academy ("Mather"), 124, 138
- Publication: 1945-46, 129; 1946-47, 137; 1947-48, 147, 150; 1948-49, 156
- Report of: 1945, 126; 1946, 134; 1947, 144; 1948, 153
- Rumford: 1945-46, 124, 129; 1946-47, 136; 1947-48, 147; 1948-49, 156
- Award for 1945, 151
- Grants: 1946-47, 143; 1947-48, 150, 152
- Report of: 1945, 126; 1946, 134; 1947, 143; 1948, 152
- School Science, 141, 149
- Statutory and Legislative Changes, 139, 148
- UNESCO, 150
- Warren, C. M.: 1945-46, 129; 1946-47, 136; 1947-48, 147; 1948-49, 156
- Grants: 1944-45, 126; 1945-46, 134; 1946-47, 143; 1947-48, 153
- Report of: 1945, 126; 1946, 134; 1947, 143; 1948, 153
- Conference on the Artist in Contemporary Society, 139
- Council, list of: 1947-48, Vol. 76 (3), i; 1948-49, 121
- Report of: 1945, 125; 1946, 132; 1947, 142
- Delegates, see Representation
- Executive Officer, appointment of, 148
- Exhibits, 140

- Fellows, list of, Vol. 76 (3), iii
 Acceptances: 1944, 123; 1946, 137; 1947, 148; 1948, 150
 Deaths: 1945, 125; 1946, 133; 1947, 142; 1948, 148, 151
 Election: 1945, 128; 1946, 132; 1947, 141, 1948, 156
 Resignations: 1944, 123; 1946, 133; 1947, 142, 148, 149; 1948, 151
 Transfer of Status: 1944, 123; 1946, 137; 1947, 148; 1948, 150
- Foreign Honorary Members, list of, Vol. 76 (3), xi
 Acceptances: 1944, 123; 1946, 137; 1947, 148
 Deaths: 1945, 125; 1946, 133; 1947, 142; 1948, 151
 Election: 1945, 128; 1946, 133; 1947, 142; 1948, 157
- Funds, see under Committee; also see Barbour Fund
 Gifts: Agassiz, 128; Barbour, 141
 Library, see Committee on Library
- Meetings
 Annual: 1945, 125; 1946, 132; 1947, 141; 1948, 151
 Conference on the Artist in Contemporary Society, 139
 Records of, 123
- Membership, alphabetical index to list of, Vol. 76 (3), xiii; see also Fellows, Foreign Honorary Members
 Officers: 1945-46, 129; 1946-47, 136, 139; 1947-48, Vol. 76 (3), i, 147; 1948-49, 121, 156
 Presidential Address, 1944, 123
 Publications, see Committee on Publication
 Records, see Meetings, Records of
 Reports, see under respective officers, committees, etc.
- Representation
 Inter-Society Committee on Science Foundation
 Legislation, 141
 National Conference on UNESCO, 141
 Royal Belgian Academy of Science and Letters, 137
- Resolutions
 Academy: Science Talent, 141
 Council: Food to Europe and Rationing, 132; UNESCO, 130
 Standing votes, rescinded, 139
 Statutes, revised, 1947, Vol. 76 (3), xix
 Amendments, 128, 129, 130, 137, 139, 148
 Treasurer, report of: 1945, 125; 1946, 133; 1947, 142; 1948, 152